Movement of mature and early life stages of the Grand River walleye (*Sander vitreus*) population in Lake Erie's eastern basin

by

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A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Science

in

Biology (Water)

Waterloo, Ontario, Canada, 2020

Author’s declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Lake Erie's commercial and recreational walleye fishery is the largest of the Great Lakes, requiring effective management to maintain a sustainable and complex fishery. Lake Erie's walleye fishery is composed of multiple spawning populations, which presents a management challenge. The movement patterns and recruitment of distinct walleye populations that make up the fishery must be considered by managers to avoid overexploitation and to maintain population diversity. The Grand River walleye population in Lake Erie's eastern basin is considered a priority for rehabilitation due to blocked access to spawning habitat by a low-head dam and degraded habitat quality. The objectives of this study were to: i) investigate movement patterns of spawning walleye in the Grand River using acoustic telemetry; and, ii) investigate movement and habitat use of young-of-the-year (YOY) walleye in relation to the Dunnville Dam and surrounding habitat segments using stable isotope analysis.

Between 2015 and 2018, 267 mature walleye were tracked in the Grand River using acoustic telemetry, and in fall of 2018 144 YOY walleye were sampled from the river via boat-mounted electrofishing. Both male and female mature walleye that were moved upstream of the Dunnville dam were found to actively migrate ~20-40 km up-river to areas with suspected suitable spawning substrate during the spring spawning season. Residence time of walleye above the Dunnville Dam and timing of return migrations suggest that the dam may be acting as an impediment to downstream movement. Of all the walleye tagged, 43% returned to the Grand River during at least one year subsequent to the initial spawning

season during which they were tagged, and those that returned were detected at spawning habitat below the Dunnville Dam during March and April. Although differences in YOY walleye stable isotope signatures (carbon and nitrogen) were evident across sampling locations in the Grand River in fall of 2018, YOY walleye were not successfully sampled in 2019 and a description of the trophic baseline was needed to infer YOY walleye movements. Condition of YOY walleye sampled during the fall of 2018 was highest at the river mouth, which may indicate relatively favourable health conditions for YOY walleye at this location.

The results of the biotelemetry study suggest that the removal of the Dunnville Dam or the construction of a functional fishway would increase access to potential additional spawning habitat, which may lead to an increase in successful spawning activity for the Grand River walleye population. Future research on YOY walleye in the southern Grand River will be necessary to enhance the understanding of how recruitment and year-class strength is impacted by movement barriers (i.e., Dunnville Dam) and variation in spawning and nursery habitat quality (i.e., abiotic and biotic stressors). Furthermore, additional analyses on mature walleye apparent annual survival and spawning site fidelity probabilities would further inform our understanding of Grand River walleye movement and support walleye management in Lake Erie’s eastern basin.

Acknowledgements

This project was supported by funding from Lake Futures, as part of Global Water Futures (Canada First Research Excellence Fund), the University of Waterloo Department of Biology, the Ontario Ministry of Natural Resources and Forestry, the Great Lakes Fishery Commission, and Canada Research Chairs (Dr. Mark Servos).

I would like to thank my supervisors Dr. Mark Servos and Dr. Rebecca Rooney for their continued guidance throughout this project. Thank you Mark for strengthening my interest in all things fishy by sharing your wealth of experience and by instilling confidence through your trust, mentorship and generosity. Thank you Rebecca for your advice and mentorship, and for always encouraging knowledge and skill sharing in your laboratory community. A special thank you to Tom MacDougall who was instrumental in shaping the path of this project and who was always open to sharing appreciated insights. Thank you to my committee members, Dr. Heidi Swanson and Dr. Simon Courtenay, for providing valuable feedback and perspective throughout this process.

To all the members of the Servos Lab and Rooney Lab, I am grateful to have been part of the welcoming and supportive community you all created. Thank you Hadi Dhiyebi and Leslie Bragg for helping teach me how to navigate the trials and rewards of field work. Thank you to all the volunteers, including Kirsten Nikel, Erika Burton, Samina Hayat, Patrick Breadner, Lucila Xaus, Jaki Peters, Sally Ju, and Erin Ford, for your hard work and positive attitude during long nights on the Grand River.

I would like to recognize the Students of the Water Institute Graduate Section, Lake Futures, and the Biology Graduate Student Association communities for enriching my graduate experience by providing opportunities for skill sharing and conversation.

Lastly, to my family and friends both near and far, thank you for believing in me, for providing a shoulder to lean on, and for so many smiles.

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1 Literature review

1.1 Lake Erie walleye

The Lake Erie walleye (*Sander vitreus*) population is made up of multiple spawning populations (or stocks) that span all three basins of the lake and that support large-scale recreational and commercial fisheries for both Canada and the United-States (Roseman et al., 2010; Walleye Task Group, 2020). The mesotrophic waters of the western, central, and nearshore eastern basins support a cool-water fish community with walleye as a key top predator. This species is of both high economic and ecological value, making its health and stability a top priority for lake managers (Walleye Task Group, 2020). One of the main management challenges for fisheries managers is distinguishing the relative contribution of each spawning population to the fishery in order to avoid overexploitation of smaller or less productive sub-populations and to conserve locally adapted populations (Kayle et al., 2015). Maintaining diverse spawning populations (multiple locally adapted reef and riverine stocks) increases the stability and resiliency of the population as a whole by increasing the capacity to respond to stressors and reducing recruitment variability (DuFour et al., 2015; Schindler et al., 2010). Accordingly, managers have recognized the need to protect and restore depressed spawning populations through restoration actions where habitat has been degraded (Kayle et al., 2015; Ryan et al., 2003).

Walleye are a migratory fish species that can move through multiple management units in the Great Lakes (Hayden et al., 2014; Wang et al., 2007; Zhao et al., 2011). Lake Erie fisheries managers must consider the dynamic movement of various walleye populations as they migrate among key habitats, including riverine and in-lake reef spawning beds, foraging areas, and refuge habitats. This is especially challenging in the eastern basin due to the mixing of eastern and western spawning populations during the post-spawning seasons (Wang et al., 2007; Zhao et al., 2011). The shallow western basin has the most productive walleye populations, including the Maumee River, Sandusky River, Detroit River, and in-lake Ohio reef complex spawning populations (Figure 1.1) (Wang et al., 2007), which make up 90% of the annual lake-wide harvest (Walleye Task Group, 2020). These populations are known to migrate into the eastern basin during the summer after spawning, where they mix with the smaller eastern basin spawning populations (including Van Buren Bay, Grand River, Lackawanna shoal, and Shorehaven Bay populations, Figure 1.1) (MacDougall et al., 2007; Matley et al., 2020; Strange and Stepien, 2007). There are five fisheries management units that span the three basins of Lake Erie, with management units 1-3 (western and central basins) having an annual total allowable catch harvest quota system, and management units 4-5 (eastern basin) being managed as a separately (Kayle et al., 2015). Currently, individual spawning populations are aggregated into eastern and western basin groups for management purposes (Kayle et al., 2015). If fisheries managers could predict where walleye move in space and time, including the movement ecology and habitat selection of locally adapted eastern basin populations compared to the migratory western basin populations, a more integrated approach to management across basins and spawning populations may be pursued (Kayle et al., 2015).

The Great Lakes Fishery Commission is a bi-national committee between Canada and the United-States that is in charge of managing Great Lakes fisheries. Each lake has a committee that is responsible for setting harvest rules for key fish species and for developing strategic fisheries management goals that specify actions outlined in their Fish Community Objectives. One of the main goals established by the Lake Erie Committee is to maintain a healthy mesotrophic community with walleye as a key top predator in the western, central, and nearshore eastern basins (Markham and Knight, 2017; Ryan et al., 2003). Some of the Fish Community Objectives listed by the Lake Erie Committee as necessary to achieving this goal are to protect and restore self-sustaining river-spawning stocks of walleye in an effort to conserve locally adapted stocks that promote genetic diversity, and to enhance fish habitat, including nearshore, riverine and estuarine habitats (Markham and Knight, 2017; Ryan et al., 2003). Some of the gaps highlighted by Lake Erie Committee are especially relevant to the complex nature of the eastern basin fishery, with recommendations to enhance understanding of fine-scale population structure of mixed-stock fisheries, including information on movement patterns and relative contribution to the fishery (Markham and Knight, 2017). Accordingly, more research was listed as needed on quality of spawning habitat, especially with relation to barriers to fish access, and on factors impacting recruitment from populations (Markham and Knight, 2017).

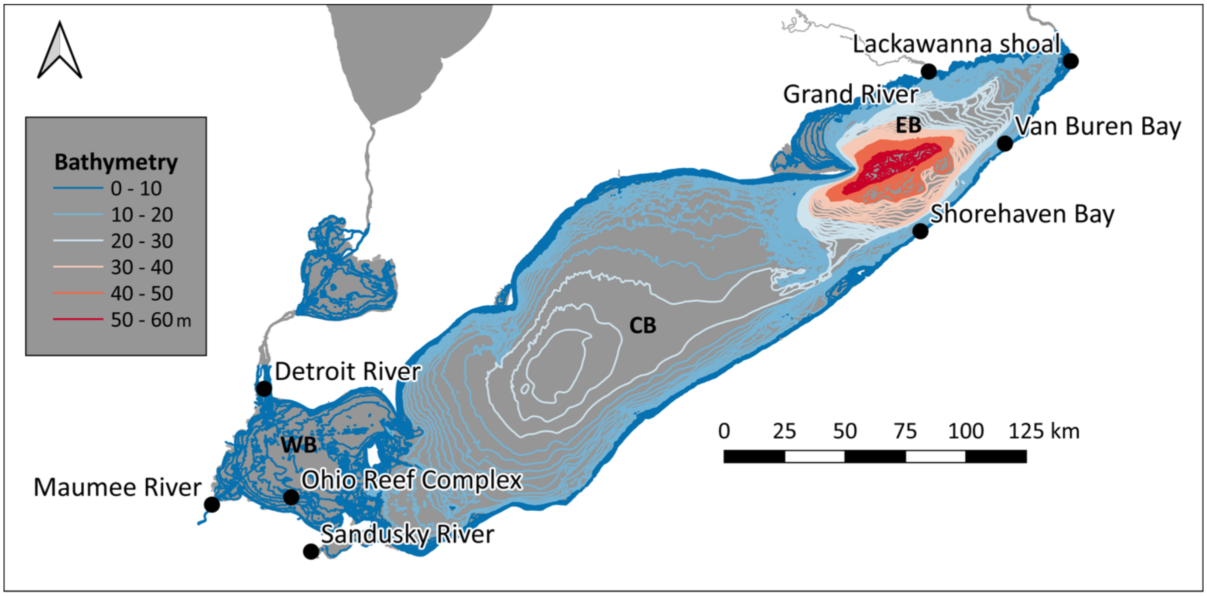

Figure 1.1: Bathymetric map of Lake Erie, including approximate locations of spawning populations of walleye (black points), and the divisions between western (WB), central (CB), and eastern (EB) basins. GIS data was provided by the Ontario Ministry of Natural Resources and Forestry and this map was made in QGIS.

1.2 Grand River walleye population

Ontario's Grand River, in the eastern basin of Lake Erie, supports a riverine spawning walleye population that was once considered the second largest in the eastern basin after Van Buren Bay (Zhao et al., 2011). However, the Grand River subpopulation of walleye has become progressively depressed due mainly to habitat degradation (MacDougall et al., 2007; Zhao et al., 2011). Studies using genetic markers have been able to discern genetic divergence of the Grand River population from other eastern basin populations (Strange and Stepien, 2007), and annual Grand River walleye movement patterns within the lake have been identified as unique (Matley et al., 2020). The Grand River is listed as a priority management area by the Lake Erie Committee, with improving fish access to spawning habitat and restoring the natural hydrological functions of river and estuary habitats as main objectives (Markham and Knight, 2017; Ryan et al., 2003). A low-head dam just 7 km upstream from the river mouth at the town of Dunnville acts as a barrier to 97% of potential suitable spawning habitat in the lower ~50 km reach of the river, with only a small portion of habitat downstream of the dam remaining available to spawning walleye (Ecologistics, 1982; MacDougall et al., 2007). Furthermore, the southern Grand River has been found to have poor habitat and water quality, which may impact migrating spawning walleye and the success of young-of-the-year (YOY) during their first growing season (MacDougall and Ryan, 2012).

Efforts to improve the Grand River stock of walleye have been mostly unsuccessful, including the creation of an ineffective fishway in 1994 and mostly unsuccessful attempts to stock the river between the 1980s and 90s (Bunt et al., 2000; MacDougall et al., 2007). The manual facilitation of mature lake-run walleye from below to above the Dunnville Dam during spring spawning runs between 2000 and 2004 led to an increase in the annual fall recruitment of YOY walleye from the river (MacDougall et al., 2007). The coincident increase in YOY walleye with increased movement of mature walleye upstream of the dam suggests that increased access to spawning habitat could lead greater production from the population (MacDougall et al., 2007). The manual facilitation of walleye over the dam during spring spawning runs has been historically conducted irregularly by a variety of groups and without a consistent protocol among years (MacDougall et al., 2007). The removal of the

Dunnville Dam has been considered by the Lake Erie Committee a strategy for the rehabilitation of the Grand River walleye population because dam removal would increase access to habitat necessary for spawning and early development (MacDougall et al., 2007; Markham and Knight, 2017).

While it is important to have suitable spawning habitat for successful reproduction, it is also critical to have suitable nursery habitat for larval and YOY walleye. Survival and growth of early fish life stages are necessary for the production of a healthy recruitment (the number of new fish that enter the fishery in a year) and are regulated by physical and biological factors that can vary spatially and temporally (Ludsin et al., 2014). YOY walleye can make extensive movements during their first year for feeding, refuge, and overwintering so it is important to consider factors that may impact YOY survival among different habitats and stages of growth. Larval walleye in the western basin of Lake Erie have been found to prefer warm nearshore habitat with high density of forage fish ichthyoplankton and lower water clarity (Roseman et al., 2005). Larval walleye from riverine spawning populations like the Maumee River rely on sufficient river discharge to carry them to the river mouth where they utilise habitats in the nearshore western basin for forage habitat during their first summer growing season (Mion et al., 1998). In contrast, the deeper eastern basin, with its narrow mesotrophic nearshore, has less habitat area suitable for YOY, and tributary recruits likely remain in the rivers for their first growing season (MacDougall et al., 2007). Ontario's Grand River YOY walleye use the river for forage habitat during their first year of growth, and are usually only found in the nearshore of Lake Erie after their first winter (MacDougall et al., 2007). However, water quality, habitat and prey availability can vary between river reaches above and below the Dunnville Dam in the southern Grand River (MacDougall and Ryan, 2012). It is unknown to what degree YOY walleye use the different sections of the river during their first year of life and how the dam impedes their movement. It is therefore necessary to continue to investigate factors influencing walleye recruitment in the Grand River, especially how YOY walleye use the river during their critical first year of growth.

1.3 Southern Grand River habitat

The Grand River watershed is the largest on the Canadian side of Lake Erie's eastern basin, draining 6800 km^2 from southern Ontario. The southern section of the watershed has erodible clay geology and a lower elevation gradient reflective of the underlying Haldimand clay plain, making the southern Grand River naturally turbid. Water quality was historically degraded due to lumber and grist mills, and today is further impacted by the cumulative inputs of nutrients and sediment from upstream agricultural and urban runoff, and shoreline development. The Dunnville Dam was built in 1829 for transportation and regulation of water levels into the nearby Welland Canal, but now has only recreational and aesthetic value. Water quality and habitat availability may be degraded by the dam due to the impacts of river fragmentation.

One of the primary forms of river ecosystem alteration worldwide is in the construction of dams (Rosenberg et al., 1997). The fragmentation of rivers by dams impacts aquatic ecosystem function by impeding habitat connectivity, modifying nutrient and sedimentation dynamics, and altering hydrology, which in turn can alter aquatic food webs

(Power et al., 1996). Dams fragment naturally free-flowing rivers into impounded lentic reaches with regulated hydrology (Poff et al., 1997). This can impact food web energy flow by inundating riparian and wetland habitats, increasing sediment and nutrient retention, and trapping autochthonous and allochthonous organic carbon (Downing et al., 2008). Furthermore, food webs may be impacted by changes to fish species abundances. Free-flowing heterogeneous river reaches tend to have greater fish diversity than impounded sections, which tend to show declines in lotic taxa (Freedman et al., 2014). At the base of the food web, the creation of reservoirs along lotic river systems introduces increased input of pelagic primary production (phytoplankton), compared to more benthic driven primary production (periphyton and aquatic vegetation) in free-flowing river reaches (Freedman et al., 2014). Dams regulate flooding, which causes channel stabilization and cuts off floodplains, functionally reducing habitat heterogeneity (Nilsson and Berggren, 2000). The benefits of riparian and floodplain zones, including increased foraging diversity and refuge habitat, are lost to river homogenization (Power et al., 1996). These changes in natural flow variation and nutrient cycling alter the trophic dynamics of the river, which can in turn impact biotic assemblages.

The degraded water quality of the southern Grand River has the potential to impact the health of aquatic organisms, including the Grand River population of walleye. Historically, water from the Grand River and Lake Erie would have mixed throughout the 30 km stretch from Cayuga to the river mouth, but the construction of the Dunnville Dam inhibited this hydrological connectivity (GRWMP-Lake Erie Working Group, 2012). Storm surges and seiches from Lake Erie would have created natural flooding events and water mixing in the wetlands and floodplains of the southern Grand River, facilitating sediment and nutrient cycling, and promoting biological diversity (GRWMP-Lake Erie Working Group, 2012). Currently, the river between Port Maitland and Caledonia is split into segments characterized by water quality and biotic assemblages: 1) the lake-effect zone between the river mouth at Port Maitland and the Dunnville Dam, 2) the reservoir from the Dunnville Dam to the town of Cayuga, and 3) the heterogeneous 'riffle' segment from Cayuga to the next dam at the town of Caledonia. Cayuga has been described as the interface between the heterogeneous upstream and the hyper-eutrophic downstream, where measurable changes in water quality occur (increases in total suspended solids, organic nitrogen, total phosphorus, nitrite, ammonia, water temperature and occurrence of lethal bottom anoxia), and changes in biotic community (increases in species tolerant of adverse conditions and standing crops of planktonic algae and cattails, and decreases in submerged macrophytes (rare to non-existent), benthic invertebrates and fish diversity) (MacDougall and Ryan, 2012). Where the river slows and deepens between Cayuga and the Dunnville Dam, sediment tends to settle while nutrients and water temperature increase, which is exacerbated by the feedback cycle between anoxia, soluble reactive phosphorus, and algae (MacDougall and Ryan, 2012).

Shifts in the biotic community surrounding the Dunnville Dam have been observed, where aquatic macrophytes and periphyton are almost completely shaded out by dense planktonic algae (Gilbert and Ryan, 2007; MacDougall and Ryan, 2012). Increased turbidity can directly impact fish and benthic invertebrates by clogging breathing structures and smothering benthic filter feeders, leading to an increase in organic pollution tolerant sediment burrowers (Henley et al., 2000). The indirect impacts of turbidity and associated declines in aquatic macrophyte diversity are a loss of nursery and shelter habitat for YOY walleye and prey fishes (Trebitz et al., 2007). Accumulated fine silts in riparian and wetland areas are susceptible to resuspension, often by species like the common carp (*Cyprinus carpio*) (Chow-Fraser, 1998). The survival of fish eggs and larvae can be sensitive to high water temperatures and associated low dissolved oxygen, high water flows, and the smothering of habitat by sedimentation (Henley et al., 2000; Mion et al., 1998). As a result of the decrease in food diversity and increase in periods of bottom anoxia in the Dunnville reservoir, sensitive species with low tolerance ranges have almost only been found upstream of Cayuga in the riffle segment (MacDougall and Ryan, 2012).

1.4 YOY walleye

Walleye in eastern Lake Erie tend to consume a mix of rainbow smelt (*Osmerus mordax*), emerald shiners (*Notropis atherinoides*), round goby (*Neogobius melanostomus*), temperate bass (family *Moronidae*), and clupeids (family *Clupeidae*) (Forage Task Group, 2009); however, walleye may prey on a diverse selection of other species depending on availability and size. YOY walleye exhibit ontogenetic shifts in feeding from zooplankton (rotifers, copepods, and cladocerans), to benthic invertebrates (mayfly nymphs), to fish as they develop from larvae to fry (Mathias and Li, 1982; Scott and Crossman, 1973). Walleye consume larger prey sizes as they grow and their gape width increases; at 30 mm length, walleye begin to consume fish and by 100 mm often become completely piscivorous

(Galarowicz et al., 2006; Mathias and Li, 1982). Shifts in diet are accompanied by the development of the tapetum lucidum, a retinal layer that allows for enhanced vision in low light (scotopic vision), which occurs between 37 mm and 140 mm length (Braekevelt et al., 1989). As scotopic vision develops, walleye will shift from littoral limnetic habitats to deeper water with decreasing light intensities, giving walleye a spatial advantage over other predators (Ali and Anctil, 1968).

First-year survival is a critical for recruitment to the population. Many abiotic and biotic factors impact YOY walleye survival, and first-year survival is highly variable within and between ecosystems. Abiotic factors, such as water temperature and river discharge, and biotic factors, such as competition for resources, predation stress and cannibalism, can all impact walleye to varying degrees in their first year of life (Ludsin et al., 2014; Mion et al., 1998; Roseman et al., 2005). Within the southern Grand River, changes in abundance of prey items and predators have been observed between river segments. MacDougall and Ryan (2012) assessed fish species relative abundance between 1999 and 2005, and found that relative numbers of gizzard shad (*Dorosoma cepedianum*), a prey species for both YOY and mature walleye (Bethke et al., 2012), were much higher in the two downstream segments of the river (Cayuga to Dunnville and Dunnville to Port Maitland compared to Caledonia to Cayuga). One of the most abundant predators of YOY walleye in these two segments was found to be adult walleye (MacDougall and Ryan, 2012), which can show cannibalistic behavior (Chevalier, 1973). However, when an abundance of forage fish is available, the frequency of cannibalism tends to decrease in walleye (Forney, 1974). The dominance of gizzard shad may protect YOY walleye from cannibalistic behaviour in the downstream segments. In contrast, in the upstream segment from Cayuga to Caledonia, insectivorous fish became more abundant, including walleye forage species like logperch (*Percina caprodes*) and shiners (family *Cyprinidae*), but not to the same degree as the abundance of gizzard shad downstream (MacDougall and Ryan, 2012). However, the abundance of smallmouth bass (*Micropterus dolomieu*) was highest in the upstream segment (MacDougall and Ryan, 2012), which is a common predator of YOY walleye, and which can often have significant impacts on YOY walleye survival (Quist et al., 2003; Santucci Jr. and Wahl, 1993). It is important to better understand how biotic factors such as prey availability and predation stress may impact the growth, health, or survival of walleye within different segments of the southern Grand River.

1.5 Methods review

1.5.1 Biotelemetry

The difficulty of directly observing aquatic environments often makes fisheries management objectives logistically challenging. Mark-recapture has historically been used as a method to track movement patterns of fish populations through space and time, with benefits such as cost-effectiveness, and the ability to also study measures of abundance, survival, and rates of exploitation (Landsman et al., 2011). However, the resolution of information provided by mark-recapture studies is not always sufficient, due to the reliance on recapture (Gowan et al., 1994). Over the past approximately 50 years, the use of biotelemetry (radiotelemetry, acoustic telemetry, passive integrated transponders), has become the dominant method for determining high resolution spatiotemporal patterns of fish movement (Cooke et al., 2016; Landsman et al., 2011). Electronic tags provide researchers the ability to remotely and continuously track fish behavior over large to fine spatial and temporal scales, which has significantly broadened and accelerated the understanding of fish spatial ecology (Cooke et al., 2013; Hussey et al., 2015). Transmitter tags are generally surgically implanted into fish, and their signal can be recorded using autonomous receivers that are employed in fixed locations or by actively tracking using a hydrophone (Klimley et al., 1998; Stasko and Pincock, 1977; Wagner et al., 2011). Acoustic transmitter tags emit a unique acoustic signal (series of sonic pulses) that is recorded when tags enter the detectable range of receivers (Stasko and Pincock, 1977). Environmental sensors can be fixed to transmitters to record biological and environmental information, such as water temperature, depth, heart-rate, and acceleration (Cooke et al., 2004). Key technological advancements, including tag miniaturization, battery longevity, hardware advancements, and incorporation of environmental sensors have increased the scope of potential information gain and led to greater accessibility and widespread adoption of telemetry methods (Cooke et al., 2013; Hussey et al., 2015). Biotelemetry has been used to better understand aquatic spatial ecology in large systems such as the Great Lakes, and on topics that include reproductive biology, homing, stocking, habitat use, the impacts of barriers and fish passage structures, and for management and rehabilitation (Brooks et al., 2019, 2017; Landsman et al., 2011).

Of the available biotelemetry technologies, acoustic telemetry has become widespread for studying fish biology and applied fisheries management questions due to operational benefits, such as relative affordability and versatility, as well as the ability to create large telemetry networks where research organizations share cross-compatible technology, increasing the range of studies across large spatial scales (Crossin et al., 2017; Hussey et al., 2015). This can be exemplified in the Great Lakes with the Great Lakes Acoustic Telemetry Observation System (GLATOS), which is a network of researchers established by the Great Lakes Fishery Commission that use acoustic telemetry to answer questions related to fish ecology and management in the Great Lakes. Several of the projects within GLATOS are focused on walleye in Lake Erie and Lake Huron, with studies on their migration within and between lakes, spawning site fidelity, survival, growth, and reproductive biology (Bade et al., 2019; Faust et al., 2019; Hayden et al., 2019, 2018, 2014; Madenjian et al., 2018; Matley et al., 2020; Peat et al., 2015). The extensive network of acoustic receivers in Lake Erie provide the opportunity to study the migratory movement of eastern basin walleye with similar methods to previous studies conducted on western basin and Lake Huron populations.

It is important to determine the acoustic detection range of receivers in a receiver array to accurately interpret the movement of tagged animals. Acoustic detection range is the distance that receivers are able to detect a tag, with detection probability negatively related to the distance between the receiver and the tag (Kessel et al., 2014). Detection range can vary depending on location and over time due to heterogeneous environmental factors like water depth, turbidity, and flow (Kessel et al., 2014). When studying the movement of fish into rivers, a gated design for receiver positioning is often used (Heupel et al., 2006). For gated designs, it is important to know the probability that a tagged fish will be detected when moving upstream or downstream past receivers (Heupel et al., 2006). Ideally, receiver range will extend the width of the river with 100% detection coverage so that all tags will be detected when they pass the 'gate'. It is therefore important to consider receiver range when deciding where to locate fixed receivers and how many to deploy.

All digital communication systems can generate false detections during the sampling period. False detections occur due to transmission error, which is when a signal recording is different from the signal sent, and can be caused by interference from signal collisions of other transmitters (close proximity detection interference) or environmental noise (Pincock, 2012). Communication systems usually have error detection techniques (an Error Detection Code) to filter out the bulk of erroneous transmissions; however, the capacity of the Error Detection Code cannot be 100% and some false detections will always be recorded (Pincock, 2012). It is therefore important to have a system to screen for false detections in receiver detection data so that data is not interpreted incorrectly. Acceptance criteria can be modeled for acoustic telemetry data to detect and remove false detections.

1.5.2 Stable isotope analysis

Stable isotope analysis can be used to track movements of various species, including fish, based on the assimilation of site-specific stable isotope signatures through diet (Hobson, 1999). Tracing the migration or origin of fish is dependent on the consumption of isotopically distinct foods among regions, which are determined by various biogeochemical processes that occur within food webs (DeNiro and Epstein, 1981, 1978). Stable isotopes of carbon ($^{13}C/^{12}C$), nitrogen ($^{15}N/^{14}N$), and sulphur ($^{34}S/^{32}S$) are predominantly used for studying movement of organisms within freshwater environments, with sulphur ($^{34}S/^{32}S$) stable isotopes often included when considering transitions to marine environments (Hobson, 1999). When using stable isotopes to study movement, it is important to determine which isotopes are best suited to the study question, and how variations in metabolic activity among tissues and life stages of an organism will impact interpretation of study results. Several studies have used stable isotope analysis to determine the origin or movement of juvenile fish species within and among river and lake freshwater ecosystems (Cunjak et al., 2005; Hobson, 1999; Kennedy et al., 2005).

Stable nitrogen isotopes can be used to infer nutritional origins or migration of freshwater organisms if there are changes among regions, for example changes in organism trophic position among regions, changes in surrounding land use (undisturbed vs agricultural), and if point-source contaminants enter the system at different spaces or times (e.g., wastewater treatment effluent) (Hobson, 1999). Heavier stable nitrogen isotopes will enrich in tissues compared to their lighter isotopic counterparts, which are preferentially excreted or respired. The stable nitrogen isotope ratio of a consumer is generally enriched compared to its diet by 3-4‰, so secondary consumers are become more enriched than primary consumers and producers, and stable nitrogen isotope ratios can be used to indicate organism trophic position (DeNiro and Epstein, 1981; Minagawa and Wada, 1984; Peterson and Fry, 1987). Previous authors found that the stable nitrogen isotope ratios of a walleye population shifted in accordance with a shift in diet – walleye went from consuming primarily gizzard shad (pelagic fish species) to consuming a mixed diet of benthic and littoral species following gizzard shad winter kill, and this shift resulted in lower and more variable stable nitrogen isotope ratios than previously more enriched ratios (Bethke et al., 2012).

Stable isotope ratios of carbon tend to be discriminated by only 0-1‰ between trophic levels of food webs (DeNiro and Epstein, 1978; Peterson and Fry, 1987). The stable carbon isotope ratios of primary carbon producers change with river morphology as hydrological processes shift from headwaters to the river mouth, and accordingly movement of consumers can be traced as their carbon signatures change with the river baseline (Finlay, 2001). The stable carbon isotope ratio of a fish reflects that of the baseline carbon sources available in their food web (terrestrial versus algal) (Peterson and Fry, 1987), which are controlled by factors that limit what isotopes of carbon are available, like water velocity, canopy cover, and light penetration (Finlay, 2001; Finlay et al., 1999). The availability of aqueous CO_2 to an aquatic plant is impacted by the diffusion boundary layer on the plant surface, which generally increases as water turbulence (current velocity) decreases (Keeley and Sandquist, 1992). When aqueous CO_2 is not limited by a thick diffusion boundary layer heavier stable isotopes of carbon (^{13}C) will be discriminated against during photosynthesis over lighter isotopes (Osmond et al., 1981). Therefore, the generally more turbulent headwater river segments, especially riffle areas, will tend to have depleted algal stable carbon signatures ($\delta^{13}C$ between -34 to -30 per mil) compared to mainstem river segments or quiet bays or pools with lower turbulence that tend to have enriched algal stable carbon isotope rations ($\delta^{13}C$ between -25 to -20 per mil) (France, 1995b; Finlay, Power, & Cabana, 1999; Finlay, 2001). These patterns are also why the stable carbon signature of benthic algae is generally enriched compared to planktonic algae (measured as particular organic matter) in lakes and reservoirs (France, 1995a). Furthermore, mainstem river segments tend to have less canopy cover than headwaters and so have greater light intensity and water temperatures, which can cause algal primary production to increase. This can further limit aqueous CO_2 availability causing enrichment of algal $\delta^{13}C$ (France, 1995b; Finlay, Power, & Cabana, 1999; Finlay, 2001).

It is important to consider how isotopic discrimination can be impacted by variable tissue turnover rates among tissues, species, and life stages of fish. Dorsal white muscle is the most commonly used tissue for stable isotope analysis of fish because it is less variable in $\delta^{13}C$ and $\delta^{15}N$, and has lower inorganic carbonate and lipid content than other tissue types (Pinnegar and Polunin, 2000). The rate of isotopic turnover tends to be negatively related to body mass, and is slowest in ectotherms (Vander Zanden et al., 2015). Compared to mature walleye, YOY walleye experience rapid growth in their first growing season, which may be important to consider when studying YOY ontogenetic diet shifts using stable isotope analysis. A laboratory isotopic diet shift experiment was conducted for YOY walleye, and the authors found the isotopic discrimination to be similar to that of other fishes ($\delta^{13}C = 0.9$, $\delta^{15}N = 1.6$), but with rapid isotopic turnover rates of $\delta^{13}C$ (half-life: 10–12 days) and $\delta^{15}N$ (half-life: ~13 days) (Schumann et al., 2018). In mature walleye, $\delta^{15}N$ ratios increase with age due to changes in metabolic processes, making age a key variable to consider in food web studies of older walleye (Overman and Parrish, 2001).

The isotopic signature of the organisms at the base of the food web can vary considerably because of processes that influence the available form and recycling of isotopes; therefore, it is important to account for variability in the isotopic baseline when interpreting differences in trophic ecology across spatial scales (Post, 2002). Trophic ecology studies often measure the stable isotope signatures of a common primary consumer, like benthic invertebrates, zooplankton, gastropods, or bivalves when also examining higher consumers like fish (Hicks et al., 2017; Jardine et al., 2014; Post, 2002). While bivalves are an ideal baseline organism for aquatic food web studies due to their long generation times, they can be difficult to find and are patchily distributed in lotic systems, so other benthic invertebrates are often used as an alternative (Jardine et al., 2014). However, benthic invertebrates do not always represent the long-term average of resources due to their often rapid tissue turnover rate, so it may be important to select more long-lived taxa, including snails and long-lived aquatic insects (Jardine et al., 2014).

1.5.3 Length, weight and condition

Understanding how abiotic and biotic factors such as water temperature, prey availability, and predation stress may impact the growth and condition of walleye within different segments of the southern Grand River will help direct rehabilitation and management initiatives. Condition is an indirect measure of energy status or general well-being based on the ratio of fish weight to the expected weight at a given length (based on weight-length relationship: $W=aL^b$ or $\log W=\log a + b\log L$) (Jones et al., 1999). Condition of fish is often used in bioassessment programs as an indicator of health, due to the assumption that fish of greater weights at given lengths are of better condition (Froese, 2006). The traditional way to calculate condition is using Fulton's condition factor (*K*), which is $K = x(W/L^3)$, where *W* is fish weight, *L* is fish length, and *x* is a scaling constant that depends on the units of measure used. The length exponent of 3.0 assumes isometric growth of the fish population, where the regression coefficient of the length-weight relationship equals 3.0 (weight increases as the cube of length). However, some populations of fish exhibit allometric growth (length exponent (b) $\neq$ 3 in weight-length relationship), where increases in length can have either a positive or negative relationship to condition depending on the value of *b* (Cone, 1989; Jones et al., 1999). The weight-length relationship can vary considerably for one population of a species depending on life stage, sex, and gonad development, which can impact how to interpret measures of condition (Froese, 2006). In these instances, other methods of measuring condition can be used, such as relative condition factor and relative weight calculations (Froese, 2006). In these instances, measured fish weight is compared to the length-specific weight calculated from standard weight-length equations for the fish population of interest.

1.6 Thesis chapters

The goal of this study was to increase the understanding of mature and YOY Grand River walleye movement at a local scale in order to inform population rehabilitation actions and improve management of the mixed-population eastern basin walleye fishery in Lake Erie. There is a need to better understand spawning migratory movement in spawning adults and YOY walleye movement to inform decisions on remedial actions, including barrier removal to increase access to important riverine habitat. Chapter 2 of this thesis focuses on my first objective, which was to use acoustic telemetry methods as part of the GLATOS network to determine the extent and timing of migratory movement of spawning walleye within the Grand River relative to the Dunnville Dam and between the river and Lake Erie. Chapter 3 focuses on my second objective, which was to determine whether stable isotope signatures of carbon and nitrogen could be used to infer movement of YOY walleye among three habitat segments in the southern Grand River. Chapter 4 gives a synthesis of the main results on walleye movement in the Grand River, provides suggestions for future study directions, and discusses the implications of this research for walleye population management in the Great Lakes.

2 Acoustic telemetry reveals impeded access to upstream spawning habitat by Dunnville Dam for Lake Erie's Grand River walleye (*Sander vitreus*) population

Contributions:

Walleye movement in the southern Grand River was monitored using acoustic telemetry methods as part of the Great Lakes Acoustic Telemetry Observation System (GLATOS). This study was designed and implemented by Tom MacDougall from the Ontario Ministry of Natural Resources and Forestry (OMNRF) as part of the Lake Erie Management Unit. Site selection, fish tagging, and receiver deployment and recovery was completed by the OMNRF team.

Hillary Austin-Quinn analyzed the dataset provided by Tom MacDougall and wrote this chapter with the support of Tom McDougall, Mark Servos, and Rebecca Rooney. Valuable review comments were provided by Simon Courtenay and Heidi Swanson.

2.1 Introduction

In large-scale, multi-stock fisheries it is important to have diverse spawning populations (stocks) to maintain a robust population that is resistant and resilient to environmental change and harvest pressure (DuFour et al., 2015). Discrete spawning populations that have unique population controlling mechanisms (i.e., reproduction time or location) dependent on the local environment increase the stability of the whole population by lessening the risk of recruitment failure and increasing adaptability to environmental and climate change (sometimes referred to as portfolio effects) (Figge, 2004; Hilborn et al., 2003; Schindler et al., 2010). Habitat loss and harvest pressures can reduce resiliency of a population through homogenization and loss of portfolio effects, which can lead to population collapse (Schindler et al., 2010). Large freshwater systems like the Laurentian Great Lakes have a diversity of habitat types that can lead to diverse spawning populations within fish populations. For example, Lake Erie walleye have both riverine and lake reef spawning populations located over a broad and heterogeneous spatial scale (three distinct basins) (Kayle et al., 2015; Stepien et al., 2018; Zhao et al., 2011) and are subject to anthropogenic disturbances that can lead to population degradation (Mapes et al., 2015).

The eastern basin of Lake Erie has multiple walleye spawning populations of varying size that contribute to the eastern basin walleye fishery in combination with migratory western basin spawning populations. Lake managers have identified the enhancement of locally adapted stocks as a priority in securing a robust walleye population (Kayle et al., 2015; Ryan et al., 2003). Lake reef spawning populations of walleye dominate larval production in the western basin, which has been correlated to the historically high inter-annual recruitment variability of Lake Erie walleye (DuFour et al., 2015). It has been suggested that increasing riverine population recruitment could lead to a more stabilized fishery (DuFour et al., 2015). The Van Buren Bay spawning population in the eastern basin is similarly the dominant source of recruitment from the eastern basin, with some riverine spawning populations having a small contribution to the population. Habitat degradation from anthropogenic stressors like land-use changes in the watershed, shoreline hardening, and damming are known to impact Lake Erie tributaries where walleye spawn. Targeting degraded riverine spawning populations for restoration and protection could lead to a more productive and resilient eastern basin walleye fishery, but first it is necessary to understand the local movement and the stressors affecting those populations.

This study focuses on the Grand River in the eastern basin of Lake Erie, where a degraded walleye population is affected by a dam that acts as a barrier to upstream spawning habitat. Recent research indicates that this population has distinct depth preferences within the lake compared to other eastern basin populations, which suggests that movement patterns are unique for this stock (Matley et al., 2020). However, details of local spatial and temporal movement ecology within the Grand River have not been investigated, especially with specific relation to spawning activity. Understanding the spawning activity of the current Grand River walleye population would help inform whether there are opportunities to increase the larval walleye production needed for population enhancement.

The purpose of this study was to determine the migratory movement patterns of the Grand River walleye spawning population at a local scale relative to the Dunnville Dam. Movement of walleye in the river was monitored using acoustic telemetry methods between 2015 and 2018. Receivers were deployed upstream and downstream of the Dunnville Dam and tagged walleye were released either above or below the barrier. The main research objectives were: (1) to determine the extent and timing of walleye migratory movement when given access upstream of the Dunnville Dam; and (2) to determine what proportion of walleye return to the southern Grand River for subsequent spawning seasons and at what time of year they return to below-dam spawning habitat. It was predicted that walleye released above the dam would move further upstream towards newly accessible spawning habitat during the spawning season and would move back over the dam toward Lake Erie for the summer foraging season. It was also predicted that a sizeable proportion of walleye would return to the southern Grand River to spawn in years after tagging due to previous evidence indicating that Grand River walleye likely exhibit spawning site fidelity, including being genetically divergent and having a relatively smaller movement range compared to other eastern basin and western basin spawning populations (Matley et al., 2020; Strange and Stepien, 2007; see also Figure A6.1 and Figure A6.2).

2.2 Methods

2.2.1 Study site

The Grand River watershed is the largest on the Canadian side of Lake Erie's eastern basin, draining 6800 km^2 of agricultural and urban land from southern Ontario. Several dams fragment what would have once been 100 km of continuous river into four stretches, now impassable for upstream migrating walleye. A low-head dam at the town of Dunnville, 7 km upstream from the river mouth at Port Maitland, acts as the first barrier to upstream movement. The dam has a main weir that crosses the river channel, and three smaller weirs to the west of the main channel that cross branches of Sulphur Creek (Figure 2.1). Only 3% (6 ha) of estimated suitable spawning habitat in the lower reaches of the Grand River occurs below Dunnville, mostly in Sulphur Creek, while the other 97% (240 ha) is between Dunnville and the Caledonia Dam upstream (MacDougall et al., 2007). The reservoir upstream of the Dunnville Dam reaches 25 km to the town of Cayuga and is hyper-eutrophic and channelized. From Cayuga to the Caledonia Dam (42 km upstream of Dunnville), the river transitions to a riffle-pool-run series that is estimated to have more suitable spawning habitat based on historical mapping (Ecologistics, 1982). The stretch of the Grand River from Caledonia to Port Maitland can therefore be split into three segments based on river morphology and connectivity: 1) the riffle segment between Caledonia and Cayuga, 2) the reservoir segment above the Dunnville Dam, and 3) the lake-effect segment from Dunnville to the river mouth.

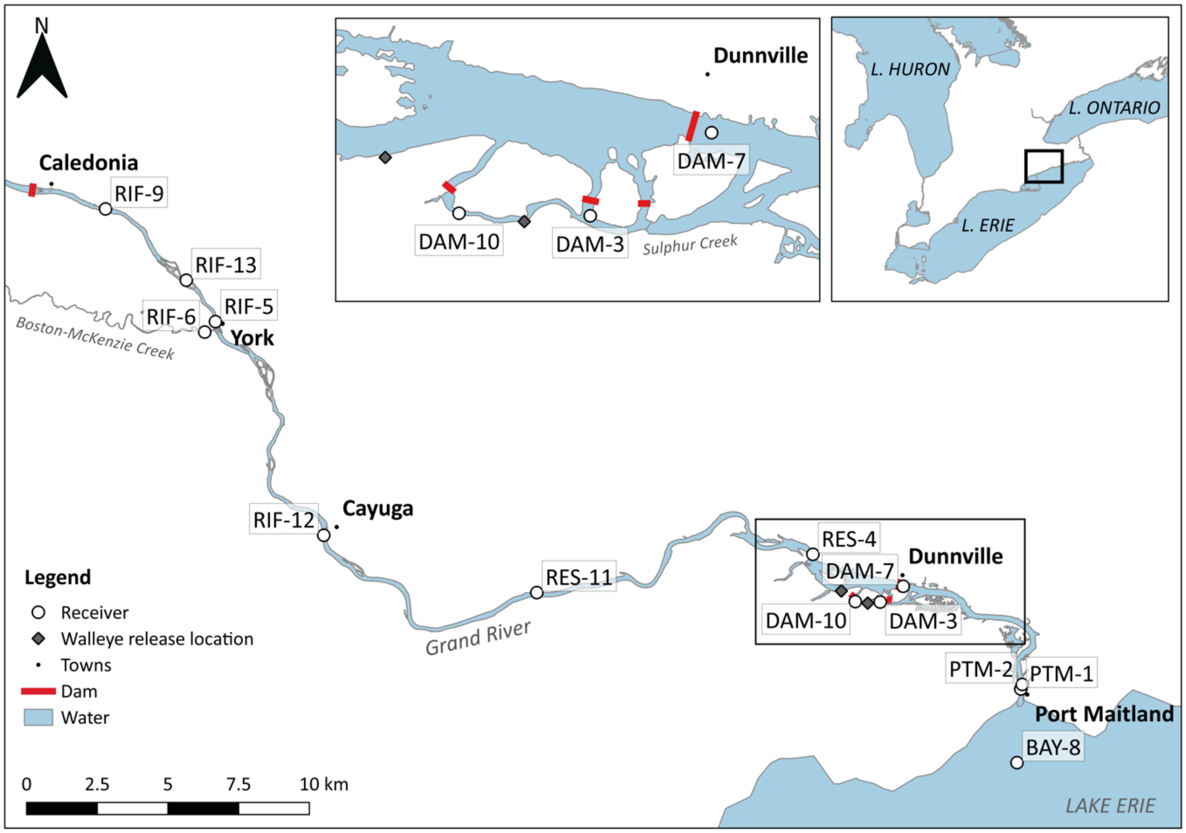

Figure 2.1: Map of study site in the southern Grand River, Ontario. Location of acoustic telemetry receivers are indicated and labelled (e.g. 'RIF-9'). Release locations of tagged walleye above and below the Dunnville Dam are indicated by black diamonds. Dams are indicated by red lines. Inset map (right) shows location of Grand River relative to Great Lakes and left inset map shows zoomed-in area around the Dunnville Dam. GIS data was provided by the Ontario Ministry of Natural Resources and Forestry and this map was made in QGIS.

2.2.2 Walleye Tagging

A total of 267 walleye were caught and tagged with acoustic transmitters in April between 2015 to 2018, with near equal numbers of males and females released above (n = 144; male = 80, female = 64) and below (n=123; male = 59, female = 64) the Dunnville Dam after being tagged (Table 2.1). Walleye were caught in spawning condition from Sulphur Creek using boat-mounted electrofishing equipment and were held in large flow-through tanks at the capture site prior to the tagging process. The sex and total length (TL) of each fish was determined before tagging, with females (mean TL = 662 mm; min = 490 mm, max = 795 mm) being on average larger than males (mean TL = 581 mm; min = 460 mm, max = 775 mm) for all years (Table 2.1). Paired t-bar anchor tags (Floy Tag Inc.) were inserted at the base of the second dorsal fin to allow for identification of internally tagged individuals. Walleye were anesthetized prior to the internal tag surgery using a portable electrosedation unit (Smith-Root, Inc., Vancouver, Washington, USA, pulsed DC, 35 V, 3 s treatment period; Vandergoot et al., 2011). Acoustic transmitter tags (Vemco model V16-4H, 86 mm x 16 mm diameter, 24 g in air, 152 db output, average nominal delay 120 s) were surgically implanted into the coelomic cavity via a small ventral incision near the centerline of the fish, which was closed using two to three interrupted monofilament sutures (Ethicon PDS-II size 2-0). Gills were irrigated continuously with water during the surgery. Immediately post-surgery, walleye were moved to recovery tanks with river water until they regained equilibrium, after which time they were released at either above or below dam release locations. All surgical tools and tags were disinfected prior to surgery. Each surgery averaged <5 min and fish were released on average <15 min after tagging. All animal handling and surgery methods followed approved OMNR animal care protocols (Ontario Ministry of Natural Resources (OMNR), 2009). If tagged walleye were harvested at any time, a monetary reward of $100 was offered as incentive to return tags to investigators.

Table 2.1: Total length (TL, mm ± standard deviation (*SD*)) and number of female and male walleye tagged and released either above or below the Dunnville Dam in the southern Grand River in 2015-2018.

		Released Above Dunnville		**Released Below Dunnville**	
Year	**Sex**	**No. Tagged**	**Mean ± *SD* TL (mm)**	**No. Tagged**	**Mean ± *SD* TL (mm)**
2015	F	14	673 ± 42	19	663 ± 54
	M	21	575 ± 42	16	565 ± 59
2016	F	17	673 ± 58	18	666 ± 48
	M	18	579 ± 44	17	603 ± 35
2017	F	15	664 ± 70	10	685 ± 63
	M	23	584 ± 80	9	525 ± 78
2018	F	18	651 ± 63	17	674 ± 42
	M	18	598 ± 24	17	613 ± 20

2.2.3 Receiver deployment and recovery

Thirteen omnidirectional acoustic receivers (VR2W, 69 kHz; Vemco, Halifax, NS) were deployed in the southern Grand River as part of the GLATOS network to detect movements of tagged walleye (Figure 2.1; Table A1.1 for raw data receiver labels). Receivers were positioned in a gated design in order to determine if and when tagged fish passed points along their migratory route in the river (Heupel et al., 2006). The two most upstream receivers, RIF-9 and RIF-13, are located 40 km and 37 km upstream from the main channel weir (DAM-7), respectively. One receiver (RIF-6) was deployed near the mouth of Boston-McKenzie Creek, a small tributary of the Grand River, just downstream of the town of York (RIF-5). RIF-12, located at the town of Cayuga, is 25 km upstream from DAM-7. Two receivers are located in Sulphur Creek downstream of the second (DAM-3) and third (DAM-10) side weirs. Two receivers (PTM-1 and PTM-2) are located at the mouth of the Grand River, 7 km downstream from DAM-7. There is one receiver (BAY-8) located 10 km into Lake Erie from the mouth of the river at Port Maitland. Receivers were deployed for varying lengths of time among years (Figure 2.2). In 2015 and 2016, only a subset of all receivers was deployed, whereas in 2017 and 2018, more receivers were deployed to increase the resolution of the study. One of the receivers near Port Maitland (PTM-1) was removed due to its proximity to the second receiver in that location (PTM-2) in 2017.

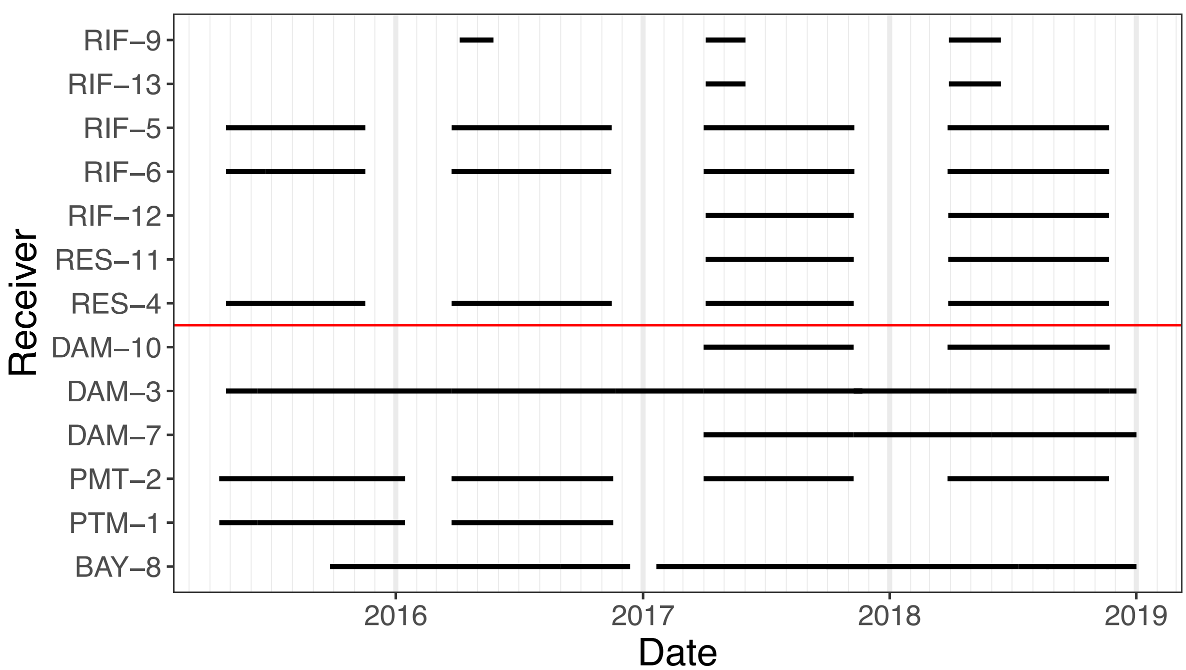

Figure 2.2: Schedule of acoustic receiver deployment in the southern Grand River. Black lines indicate when the receiver was deployed in the river. Receivers are ordered by location from upstream to downstream, and the red line indicates the break between above and below the Dunnville Dam relative to the receivers. Minor grid lines indicate month.

For this study, receiver range testing has not yet been conducted (prevented by COVID-19 pandemic). However, receiver locations were determined based on considerations of the river morphology, with the goal of avoiding locations with high flow and physical obstructions. However, the river becomes shallow and heterogenous upstream of Cayuga, with pools and riffles acting as possible obstructions to receiver detection range. During high flow events, receiver range may be compromised, especially upstream of Cayuga. Interpretation of the data from this study must therefore be considerate of potential variations of range detection probability among receivers and over time.

2.2.4 Data analysis

All data analyses were conducted in R version 3.6.3 (R Core Team, 2020). When using VEMCO acoustic tags with an average nominal delay of 120 seconds, it is recommended to remove detections when they are not accompanied by another detection from the same transmitter within an hour time interval (30 times the average nominal delay of tag) on the same receiver (Pincock, 2012). Before data analysis, all detection data for this project were screened for false detections using the Vemco acceptance criteria, with 99% of the detections accepted as true and false detections removed for data analyses. Apparent mortality events were identified, and those individuals were removed depending on analysis. Apparent mortality was defined as individuals detected on one receiver consistently for more than three months, and not detected on a different receiver >1 km away afterwards. There were eight fish released in 2015 with short tag lives (estimated tag life <397 days), which were removed from certain analyses as outlined below (see Table A1.2 for tag lives).

To investigate the first objective of determining walleye movement when given access above the Dunnville Dam, detection data were filtered for walleye released above the dam for each release year (referred to as above-dam walleye going forward). Analysis of above-dam walleye detection data was separated between 2015-2016 and 2017-2018 due to an increase in the number of receivers deployed upstream of Dunnville in 2017. For each year, analysis of detection data was focused on only walleye released in that year. This was done to avoid mixing the movement of above-dam walleye in the year of interest with those that might have stayed above the Dunnville Dam from a previous release year. In order to determine if walleye moved upstream from their initial above dam release location toward suspected spawning habitat in the riffle segment, the proportion of individual above-dam walleye that were detected at each receiver out of the total released in the year of interest was measured for all years. The proportion of individual above-dam walleye that were detected at a receiver during each season out of the total detected at that receiver in all seasons was measured to determine at what time of year walleye move to upstream receivers. This was done with years pooled, and seasons were defined as spring (March to May), summer (June-August), fall (September to November) and winter (December to February). The proportion of individual male and female walleye detected at each receiver was compared, with years pooled, because spawning activity is known to be different between walleye sexes.

The total amount of time (residence time) above-dam walleye were detected at a receiver was compared among receivers and between sexes. Residence time was calculated as the sum of the length of all detection events at a receiver for an individual walleye. A detection event was defined as the time between the first and last of a series of sequential detections on the same receiver before a detection occurred on a different receiver, or there was a time separation of at least 24 hours before another detection occurred on the same receiver. A long time-separation may indicate that the fish has moved to another area that is not in receiver range and then returned to the previous area. Residence time was calculated for above-dam walleye released in 2017 and 2018 because these years had the greatest number of receivers deployed. Apparent dead fish were removed from the dataset for this analysis. Total residence time was compared among receivers with at or near 50% or greater of the number of above-dam walleye detected in either 2017 or 2018. Total residence time during April and May was compared among the chosen receivers and between sexes using a two-way ANOVA. Because assumptions of a parametric test could not be met (normal distribution and homogeneity of variance), a permutated two-way ANOVA (n=5000 permutations) was used. The permutation test does not require the data to be normally distributed because it does not assume the distribution from which the data were drawn (Manly, 2006). A p-value is produced by examining the proportion of iterations that produce a test statistic as or more extreme than the original test statistic, and functions identically to the p-value of a parametric testing procedure (Manly, 2006). Permutation tests have been proven to be of greater statistical power than other non-parametric testing procedures

(Zimmerman and Zumbo, 1993). A p-value of 0.05 was used for this test, and if the interaction between sex and receiver was not significant, an additive model was used (interaction term was removed). A post-hoc Tukey HSD test was used to elucidate significant pairwise comparisons.

To determine the migration timing of above-dam walleye as they move upstream towards spawning habitat and then downstream towards the river mouth, the first detection, or arrival date, of walleye at four key receivers was determined in 2017 and 2018. The median arrival date ± the interquartile range was reported for walleye that were detected at the RES-4, RIF-12, RIF-5, DAM-7, and PTM-2 receivers. These receivers were chosen to represent the arrival of above-dam walleye at the reservoir segment after being released, followed by their movement to the riffle segment upstream of Cayuga, and then the first arrival below the dam and at the river mouth.

To investigate the second objective, which was to determine the proportion of walleye that return to the southern Grand River after their first spawning season and the timing of their return, a compact encounter history of walleye presence or absence in the river was first assembled. The presence (1) or absence (0) of walleye at all receivers in the southern Grand River array, except for the receiver outside of the river (BAY-8), was recorded in each year of the study, and summarized as an encounter history. For example, an encounter history of "1100" indicated an individual that was tagged in the river in 2015, was detected again the following year in 2016, but was not detected in 2017 or 2018. The number of each encounter history was compared between sexes and release location. The proportion of individuals from each tagging year that returned in either one, two, three, or any subsequent years was calculated. The proportion of individuals detected in a year out of the total individuals tagged in any previous year was also calculated. Fish that were detected as having a mortality event within the southern Grand River array and fish with short tag lives were removed from the dataset for this analysis. Next, to visualize migration patterns of walleye that return to the river, monthly counts of individuals at receivers downstream of the Dunnville Dam (pooled for all years) were plotted. Detections of walleye in their first spawning season that they were released (April and May) were removed to focus on movement patterns during their return migration. Receivers downstream of the side weirs (DAM-3 and DAM-10) were grouped and the two receivers near the river mouth at Port Maitland (PTM-1 and PTM-2) were grouped. Lastly, based on the results of the previous analysis, the median arrival date of walleye returning to the Dunnville Dam was determined for 2016, 2017, and 2018. This was focused on the DAM-3 receiver because it was deployed in the river year-round for all years of the study, and is located in Sulphur Creek, which is where suitable spawning habitat is most likely to occur.

2.3 Results

Between 2015 and 2018, a total of 3,289,530 detections from 264 of the 267 tagged walleye were recorded at the 13 receivers in the southern Grand River array (3 tagged walleye were never detected on any GLATOS receiver). Of the total detections, 7% were recorded at the seven receivers above the Dunnville Dam. Five walleye of the 264 stayed above the Dunnville Dam for >1 year (see Table A2.1 for walleye identification and Figure

A2.2 for detection histories). There were 31 walleye that were harvested and so had their tags returned, and 9 walleye that appeared to have died or dropped their tags (three of which died at receivers outside of the Grand River array; see Table A2.1 for walleye identification and Figure A2.1 for detection histories).

2.3.1 Walleye released above Dunnville

Of the walleye released above the Dunnville Dam after tagging (n=35 in 2015, n=35 in 2016, n=38 in 2017, n=36 in 2018), the proportion that were detected at each receiver was similar among years (Figure 2.3). The proportion of walleye detected at the receivers in the reservoir segment (RES) and at the most downstream receiver in the riffle segment (RIF-12) was 60-100% and decreased to 6-53% at the other upstream riffle receivers (Figure 2.3). Among the four most upstream riffle receivers (RIF-6,5,13,9), the proportion of individuals detected was highest at RIF-5 for all years except for 2018, which had the highest proportion detected at RIF-13 (Figure 2.3). Among the receivers below the Dunnville Dam, the proportion detected was highest at the main channel weir (DAM-7, 50-64%) and dropped to less than 8% at the side weirs (DAM-10 and DAM-3) (Figure 2.3). The proportion of walleye detected at the river mouth was 47-61% (PTM-1 and PTM-2) and dropped to 37-45% at the receiver in the bay (BAY-8) (Figure 2.3).

A

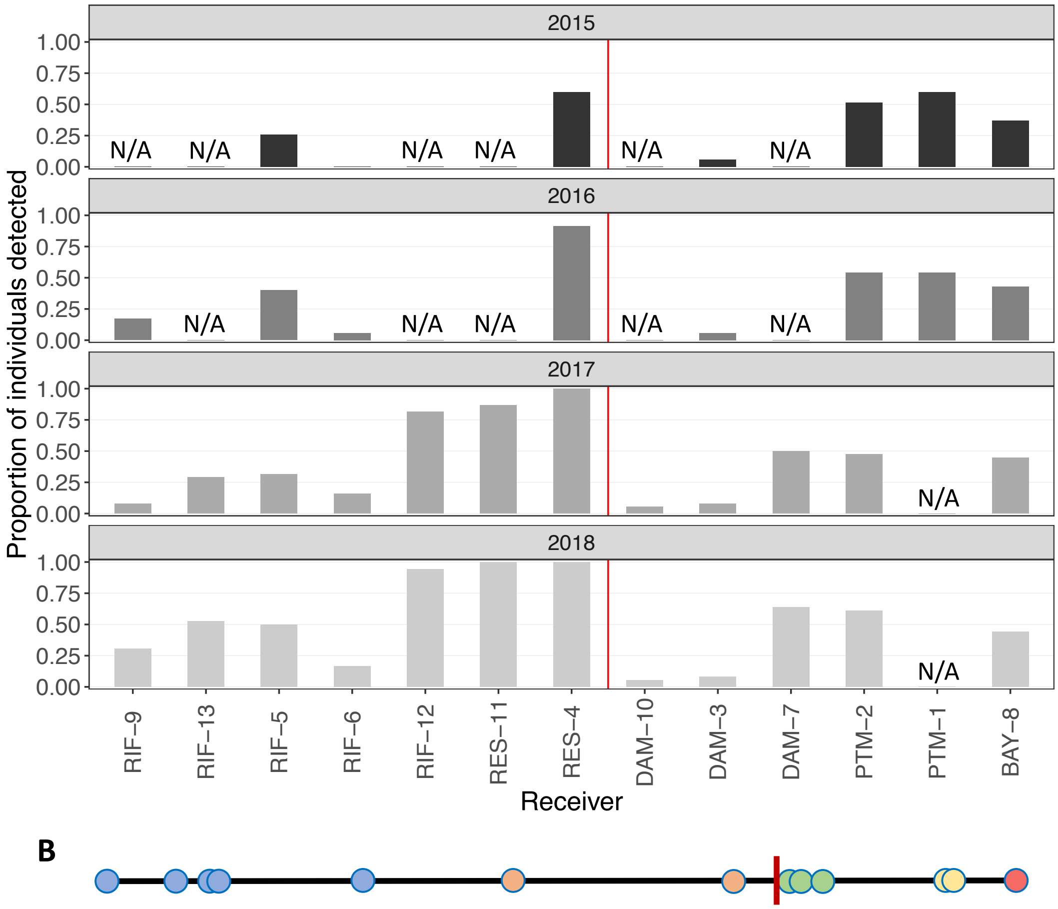

Figure 2.3: A) The proportion of walleye that were released above the Dunnville Dam that were detected at each receiver out of the total number released above the Dunnville Dam in each year. N/A indicates when a receiver was not deployed in a year. Receivers are ordered by location in the river from upstream to downstream. The red line indicates the location of the dam relative to receivers. B) Scale bar indicating the relative distance among receivers (coloured points) ordered from upstream to downstream, with colour indicating the prefix of receiver labels (blue for RIF, orange for RES, green for DAM, yellow for PTM, and red for BAY).

The proportion of walleye released above the Dunnville Dam that were detected at a receiver was different among seasons grouped for all years, excluding 2019 detections (Figure 2.4). At receivers above the Dunnville Dam, the percent of released walleye detected was greatest during the spring (84-100%), which coincides with the walleye spawning season (March to May) (Figure 2.4). Walleye that were detected at receivers above the dam in the fall were also detected above the dam the following year. The greatest proportion of walleye detected at the main channel weir was during the spring, whereas at the side weirs the greatest proportion was during the fall and winter (Figure 2.4). At the receivers at the river mouth and in the bay, the greatest proportion of walleye detected was during the spring and then fall (Figure 2.4).

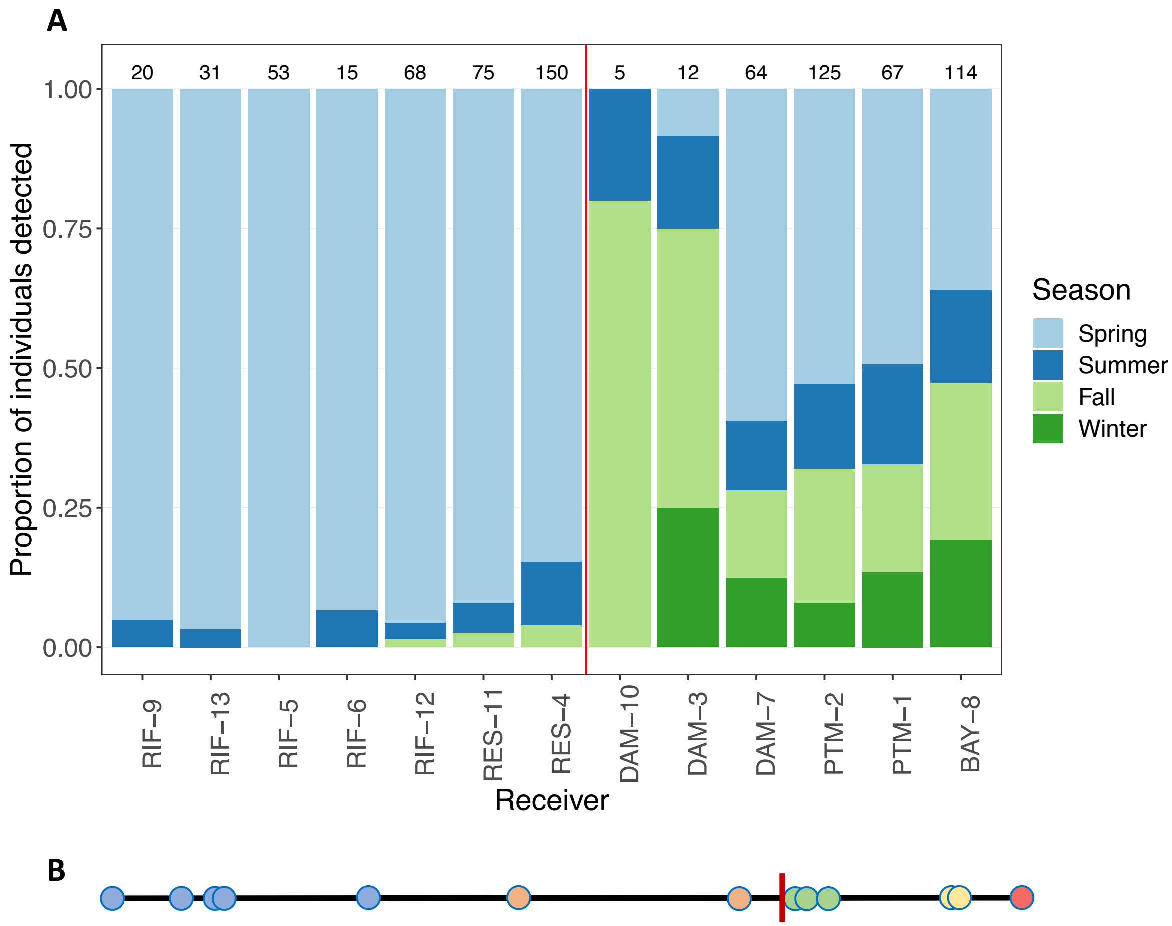

Figure 2.4: A) The proportion of walleye that were released above the Dunnville Dam that were detected at a receiver during each season out of the total detected at that receiver in all seasons (n indicated on bar), with years pooled, in the southern Grand River. Seasons are split up into spring (March to May), summer (June- August), fall (September to November) and winter (December to February). Note receivers were not deployed for equal time. Receivers are ordered by location in the river from upstream to downstream. The red line indicates the location of the dam relative to receivers. B) Scale bar indicating the relative distance among receivers (coloured points) ordered from upstream to downstream, with colour indicating the prefix of receiver labels (blue for RIF, orange for RES, green for DAM, yellow for PTM, and red for BAY).

The proportion of male to female walleye released above the Dunnville Dam that were detected at each receiver was a ~50-50% split for DAM-10, RIF-12, RIF-5, and RIF-13, and ~55-45% split for BAY-8, PTM-1, PTM-2, DAM-7, RES-4, and RES-11. RIF-9 was split 60% males to 40% females, DAM-3 had 70% males and 30% females, and RIF-6 had 70% females and 30% males (Figure 2.5).

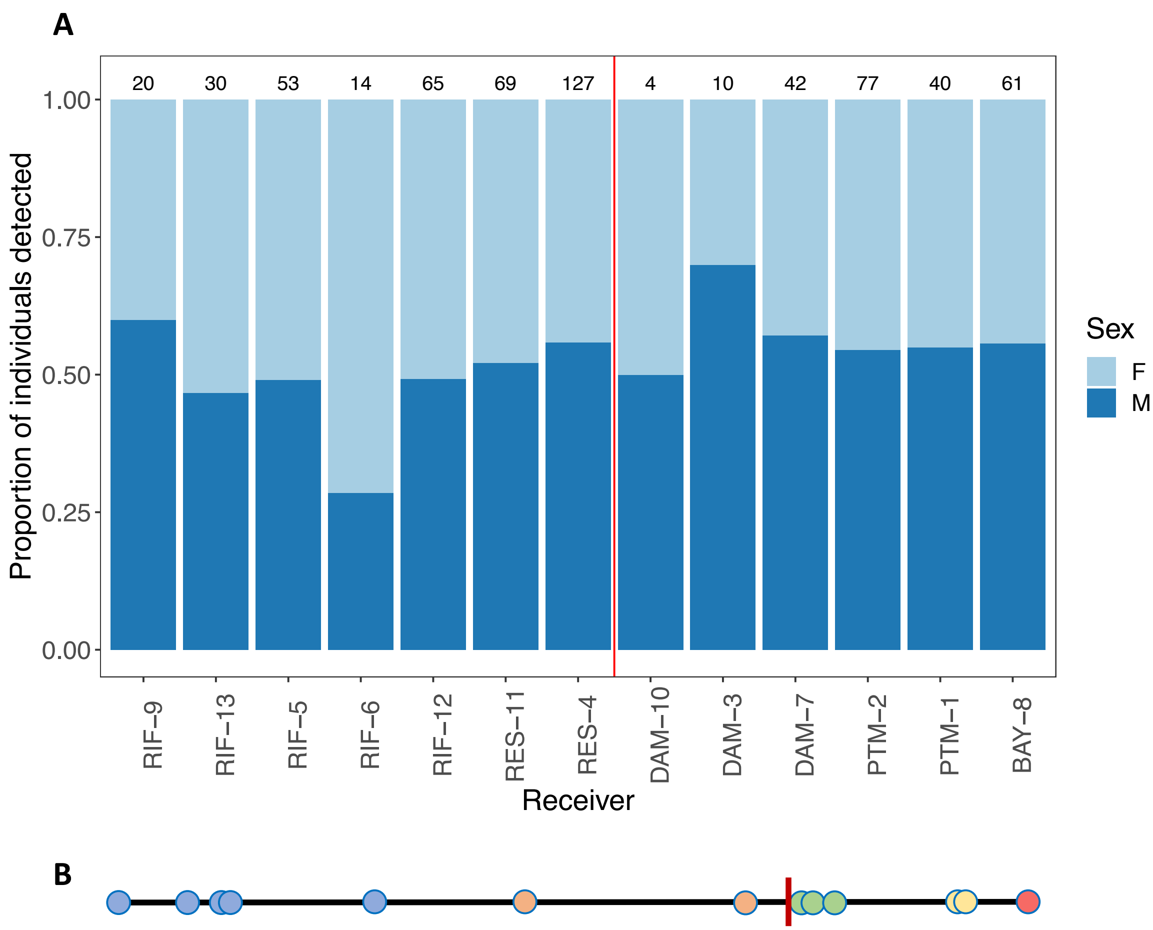

Figure 2.5: A) The proportion of male versus female walleye (only those released above the Dunnville Dam) detected at a receiver out of the total detected at that receiver for all years (n indicated on bar) in the southern Grand River. Receivers are ordered by location in the river

from upstream to downstream. The red line indicates the location of the dam relative to receivers. B) Scale bar indicating the relative distance among receivers (coloured points) ordered from upstream to downstream, with colour indicating the prefix of receiver labels (blue for RIF, orange for RES, green for DAM, yellow for PTM, and red for BAY).

The total residence time of above-dam walleye at seven receivers between April and May was significantly different among receivers (Permutation ANOVA: $F_{(7,356)}=13.05$, $p<0.0001$) and was not significantly different between sexes (Permutation ANOVA: $F_{(1,356)}=0.40$, $p>0.5000$); the interaction between the two terms sex and receiver was not significant (Figure 2.6;

Figure A3.1 for model residuals). A Tukey's HSD post-hoc test revealed significant ($p<0.05$) pairwise difference between RIF-5 and PTM-2, RIF-5 and BAY-8, RIF-5 and RES-11, RIF-5 and RES-4, BAY-8 and DAM-7, BAY-8 and RIF-12, BAY-8 and RES-11, BAY-8 and RIF-13, RES-11 and RES-4, RIF-12 and RES-4, RIF-13 and RES-4, PTM-2 and RES-4, and DAM-7 and RES-4 (Figure 2.6). See appendices for sample sizes and summary statistics of male and female walleye residence time among the selected receivers (Table A3.1).

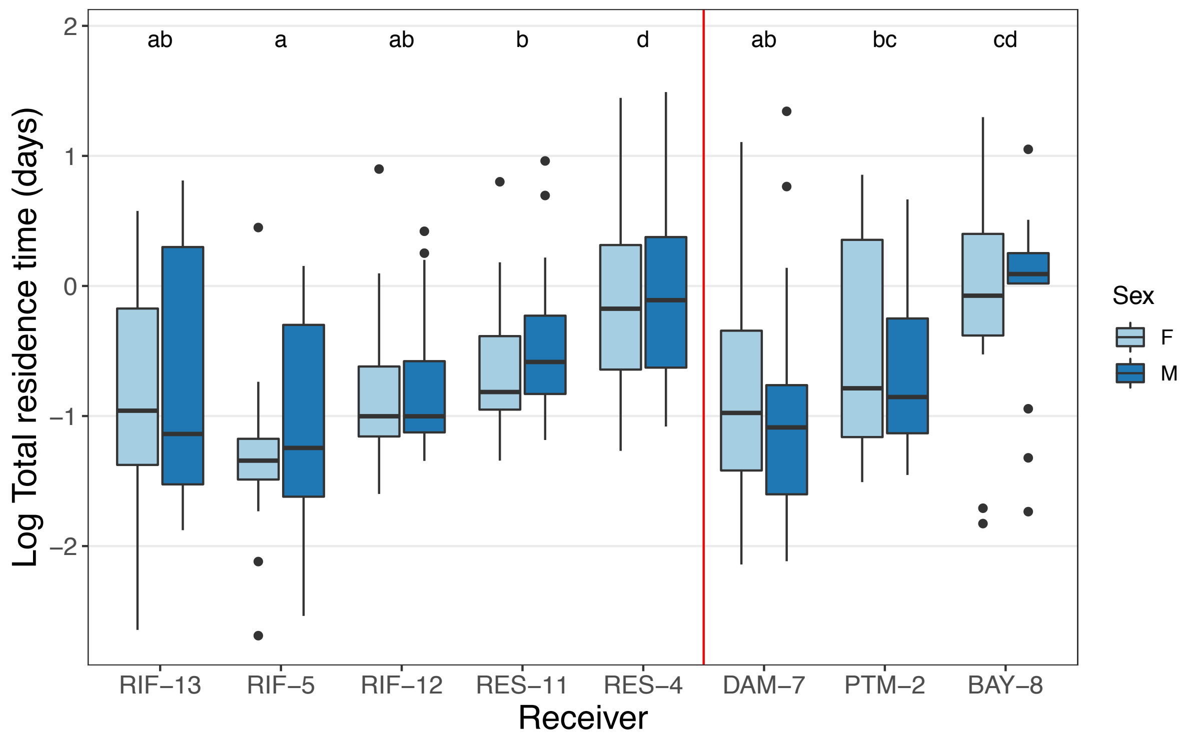

Figure 2.6: Log Total residence time (days) between male and female walleye detected at eight receivers in Grand River in 2017 and 2018 (only receivers that had >50% individuals detected (Figure 3), and only detections recorded during April and May).

Walleye were released above the Dunnville Dam over a period of three days in 2017 (April 11, 12, and 13) and six days in 2018 (April 5, 6, 9, 10, 11). The median arrival date (date of first detection) of walleye at RES-4 was on April 12 (IQR=1 day, n=38) in 2017 and April 7 (IQR=3 days, n=36) in 2018, with subsequent median arrival dates at RIF-12 on April 14 (IQR=2 days, n=31) and April 9 (IQR=4 days, n=34) and at RIR-5 on April 17 (IQR=1 day, n=12) and April 20 (IQR=12 days, n=18), respectively (Figure 2.7). Median arrival below the Dunnville Dam at DAM-7 was earlier in 2017 (April 27, IQR=18 days, n=19) than 2018 (May 8, IQR=14 days, n=23), and median arrival near the mouth of the river (PTM-2) was April 27 (IQR=17 days, n=18) in 2017 and May 20 (IQR=20 days, n=22) in 2018 (Figure 2.7). See the appendices for median arrival times at other receivers for above dam walleye released in 2017 and 2018 (Table A4.1).

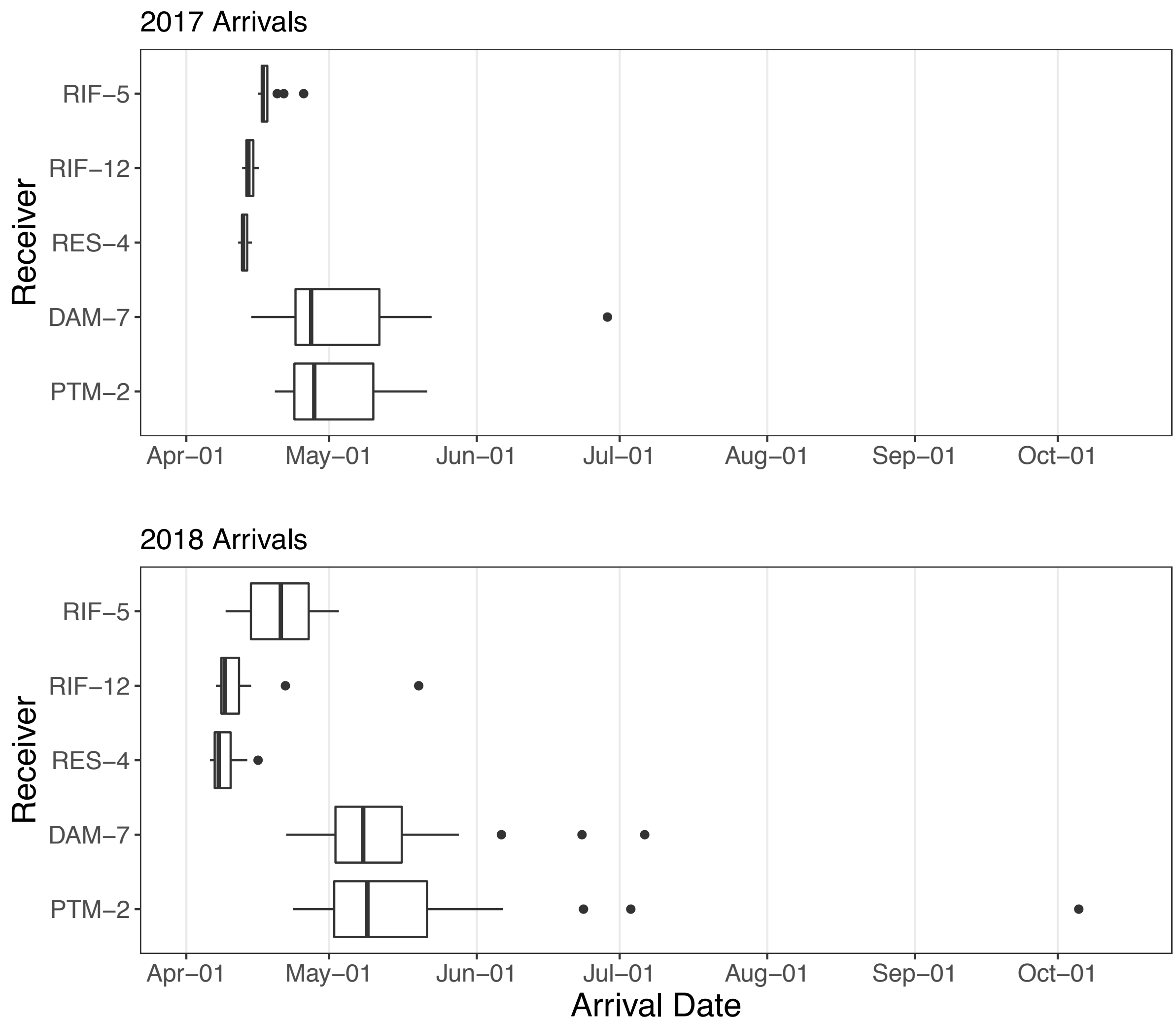

Figure 2.7: Arrival date of walleye released above the Dunnville Dam in 2017 and 2018 at four receivers, RIF-12, RES-4, DAM-7, PTM-2, in the southern Grand River.

2.3.2 Walleye that return to the river

After filtering out fish with short tag lives and fish identified as having likely died at a receiver in the Grand River array, an encounter history of walleye in the river was constructed. Of the walleye tagged in 2015 (n=58), 62% were only detected in 2015 (n=36), 21% were detected in all three subsequent years (n=12), 7% were detected in two subsequent years (n=4), and 10% were detected in one subsequent year (n=6) (Table 2.2). Of the walleye tagged in 2016 (n=68), 56% were only detected in 2016 (n=38), 34% were detected in the two subsequent years (n=23), and 10% were detected in only one subsequent year (n=7) (Table 2.2). Of the walleye tagged in 2017 (n=56), 52% were only detected in that year (n=29), and 48% were also detected in the following year (n=27) (Table 2.2).

In total, of all the walleye released in 2015, 2016, and 2017 analyzed for their encounter history (n=182), 43% (n=79) were detected during at least one year subsequent to the year they were tagged and 57% (n=103) were never detected in a subsequent year. Of the 103 walleye that did not return to the southern Grand River in any year after tagging, 48% were males (n=49), 52% were females (n=54), 51% were released above Dunnville (n=53), and 49% were released below Dunnville (n=50) (Table 2.2). For the 79 walleye that did return to the river for at least one more year after tagging, 58% were males (n=46), 42% were females (n=33), 56% were released above Dunnville (n=44), and 44% were released below Dunnville (n=35) (Table 2.2).

Table 2.2: Encounter histories of male and female walleye tagged and released above Dunnville and below Dunnville in 2015 (n=58), 2016 (n=68), and 2017 (n=56) detected at receivers in the southern Grand River array from 2015 to 2018 (excluding the receiver in the

bay, BAY-8). The encounter history code indicates presence (1) or absence (0) in the river during each year.

Tagging Year	**Encounter History**	**Female Above**	**Female Below**	**Male Above**	**Male Below**	**Total**
2015	1000	5	14	7	10	36
	1100	0	1	3	1	5
	1001	0	1	0	0	1
	1110	2	0	0	1	3
	1011	0	0	1	0	1
	1111	4	2	4	2	12
2016	0100	11	9	10	8	38
	0110	1	3	2	0	6
	0101	0	0	0	1	1
	0111	4	5	6	8	23
2017	0010	9	6	11	3	29
	0011	6	4	11	6	27

Of the walleye tagged between 2015-2017 that returned to the southern Grand River, the number detected in the river was highest during April for all receivers between 2015 and 2018, except for the BAY-8 receiver where the highest count of walleye occurred in January (Figure 2.8). For all receivers, the lowest number detected occurred during a month between June and September (note that PTM-1&2 were not ever deployed in February and only deployed in January for a short period in 2016, so the lowest number of walleye detected after those two months was August for that group) (Figure 2.8).

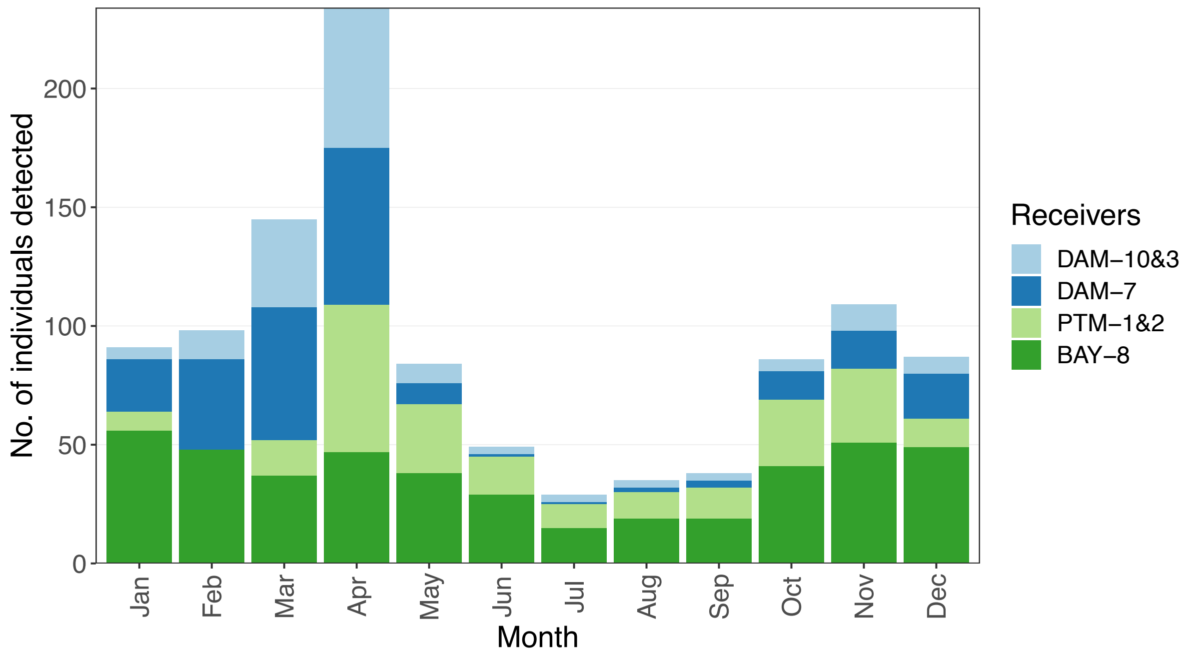

Figure 2.8: The number of individual walleye detected at receivers binned by month between 2015-2018 for walleye tagged between 2015-2017 that return to the Grand River, not including detections from the spawning season of their initial release. Note that not all receivers are deployed for equal time.

Of the walleye that were detected in the Grand River during at least one additional year subsequent to that which they were tagged (this includes walleye released above and below the dam), most were first detected at Sulphur Creek, specifically DAM-3, in the late winter or early spring (February – April). Walleye that were tagged during the 2015 spawning season that returned to the southern Grand River were found to have a median arrival date at the DAM-3 receiver in 2016 on March 12 (IQR=18 days, n=17) (Figure 2.9). Walleye tagged in 2015 and 2016 that returned to the southern Grand River for the 2017 spawning season were found to have a median arrival date at DAM-3 on March 29 (IQR=34 days, n=33) and those tagged in 2015, 2016, and 2017 that returned to the river for a subsequent spawning season in 2018 had a median arrival date at DAM-3 on April 2 (IQR=45 days, n=48). There were nine outliers, which consisted of two fish that stayed at the DAM-3 receiver for most of the year (arrival date between June 1^{st} and August 1^{st}; one male, one female), and seven fish that migrated to DAM-3 in the fall (arrival date between October 28^{th} and January 1^{st}; five male, two female) (see appendices for full detection history of each walleye that returned to the DAM-3 receiver (Figure A5.1).

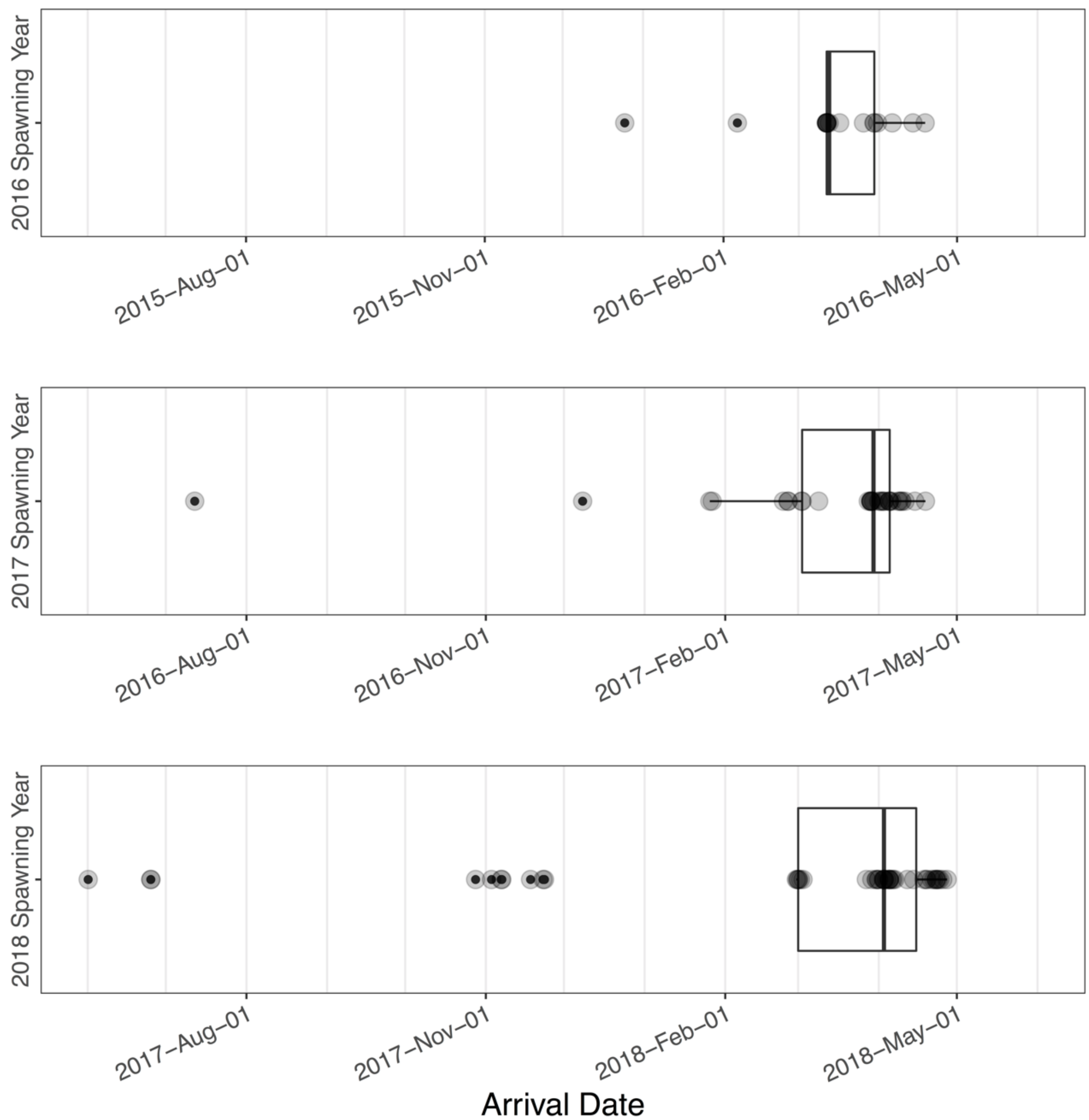

Figure 2.9: First arrival date of walleye tagged in the years previous to the spawning year indicated at the DAM-3 receiver in the Grand River array.

2.4 Discussion

This study used acoustic telemetry to assess the spawning migration of the Grand River walleye population at a local scale relative to the Dunnville Dam, which is a current impediment to movement. Both the timing and extent of walleye movement when given access above the Dunnville Dam indicated that walleye primarily utilize this upper section of the river for spawning in spring, and not for summer foraging or winter refuge activities. Walleye that return to or stay in the river after being tagged (excluding those that stay upstream of the Dunnville Dam for more than one year) return to spawning habitat below the Dunnville Dam predominantly between March and April, but as early as November. This study suggests that the Grand River walleye population would utilize upstream spawning habitat if river connectivity was restored through the removal of the Dunnville Dam or the construction of a functional fish passage, which could lead to a larger spawning population.

The results of this study indicate that the upstream spring spawning migration of walleye in the Grand River is continued when individuals are transferred past a barrier to movement. The Grand River spawning population is known to spawn in the spring and congregate below the Dunnville Dam in Sulphur Creek, where a small area of potentially suitable spawning habitat exists (Ecologistics, 1982; MacDougall et al., 2007; Matley et al., 2020). When walleye were moved above the Dunnville Dam into the reservoir segment, where no suitable spawning habitat likely exists, almost all walleye were found to migrate at least as far as Cayuga within approximately two days (25 km upstream of Dunnville), where the river begins to have more riffle-pool sequences and where suitable spawning habitat is suspected to exist (Ecologistics, 1982). Walleye were almost exclusively detected at these upstream receivers during the spring. The active movement of at least a 25 km distance upstream of the Dunnville Dam during the spring suggests that the Grand River walleye are migrating to form spawning aggregations somewhere between Cayuga and the next dam at Caledonia. The exact location of spawning grounds and the quality of spawning habitat, as well as the recruitment from these upstream habitats, remains undetermined. However, previous active facilitation of walleye over the dam was found to lead to an increase in young-of-the-year walleye recruits from the Grand River, suggesting that successful spawning can likely occur at spawning habitats above the dam (MacDougall et al., 2007).

The timing of above-dam walleye movement and the differences in residence time among receivers suggest that walleye begin their downstream migration immediately after spawning, but that the Dunnville Dam may be acting as an impediment to downstream movement during their return migration. Walleye were found to have a shorter residence time at receivers in the riffle segment relative to their residence time at receivers in the reservoir and below dam river segments during the 2017 and 2018 spawning seasons (April and May), which suggests that walleye do not linger at spawning beds. Most walleye were soon found to be detected on receivers in the reservoir segment followed by the receiver below the main weir after being detected on receivers in the riffle segment. However, the time differences between median arrival dates at receivers were longer going downstream than upstream (time difference travelling downstream between the RIF-5 and DAM-7 receivers was 10 days in 2017 and 18 days in 2018, compared to time differences of 5 days and 14 days travelling upstream between RES-4 and RIF-5 in 2017 and 2018, respectively). This may indicate that walleye are slower during their downstream migration towards the river mouth than their upstream migration. This evidence in combination with the walleye's relatively high residence time at receivers in the reservoir segment compared to receivers in other segments suggests that walleye linger in the reservoir segment before reaching the river mouth or Lake Erie during their return migration. Walleye are likely looking to begin feeding soon after spawning and may linger in the warmer reservoir segment to feed during their return migration. It is also possible that the Dunnville Dam may be acting as an impediment to downstream movement. Walleye are known to have relatively slow swimming speeds compared to other migrating fish and are disinclined to jump from low to high intensity activity (Peake et al., 2000). When walleye are confronted with the main Dunnville weir while swimming downstream they may not be inclined to increase their swimming effort to move over the weir. However, a prolonged stay in the reservoir segment may cause metabolic stress to walleye if there are high temperatures outside of their thermal optima (20-23 °C; Hokanson, 1977), which can occur in the reservoir (MacDougall and Ryan, 2012). Walleye in the Maumee River in Lake Erie's western basin were found to prefer intermediate temperatures and low discharge during their spawning migration (Pritt et al., 2013), which is reflective of the slow swimming speeds of walleye (Peake et al., 2000) and their ideal temperature range for growth potential (10 – 20 °C) (Budy, Baker, & Dahle, 2011). Future research should monitor environmental variables, including water temperature and flow in the river to determine whether there is a correlation between environmental variables and the timing of walleye movement during both their upstream and downstream migration. Walleye may require a high temperature or flow event to trigger their movement over the dam.

Male walleye from Lake Erie's Ohio reef complex and Maumee River spawning populations have been found to arrive at spawning sites earlier and leave later than females (Bade et al., 2019; Pritt et al., 2013). The proportion of male and female walleye detected at receivers above the dam was near equal and sex did not significantly impact the total residence time of walleye at receivers during the spring, indicating that both sexes have similar movement patterns within the river. This may be because near equal numbers of male and female walleye were manually moved over the dam at the same time in each year. If walleye were able to migrate upstream freely it is possible that there would be detectable difference in migration time and residence time between sexes, with males possibly migrating earlier than females.

When focusing on the 43% of walleye that were detected at receivers below the dam during years subsequent to their initial tagging year, variations in the number of individuals detected at receivers throughout the year indicate that walleye do migrate to Sulphur Creek during the spawning season, mostly arriving at the DAM-3 receiver during March and April. Slightly more males than females (~60:40) and slightly more of those released above Dunnville compared to those released below Dunnville (~60:40) returned to the river. Of the seven walleye that returned to Sulphur Creek in the fall/winter rather than spring, five were males. This may indicate that some males return to the below dam spawning habitat earlier than females. Future research on this dataset should investigate the probability of walleye returning to the Grand River to spawn, and how factors like sex, release location, and fish length affect that probability. The likelihood of individuals returning to the same spawning site over subsequent spawning seasons is a measure of spawning site fidelity (Binder et al., 2015; Hayden et al., 2018). Previous studies have found other walleye spawning populations in Lake Erie and Lake Huron, including the Maumee River, Tittabawassee River, and Van Buren Bay populations, exhibit high site fidelity, with more isolated spawning populations having higher site fidelity than those in close proximately to multiple spawning locations (Hayden et al., 2018; Zhao et al., 2011). A detection event of an acoustically tagged walleye can be treated the same way as a recapture event for jaw-tagged walleye, and so the long-term capture-recapture data can be modeled to estimate probability of annual survival and site fidelity (for example, Cormack-Jolly-Seber open-population models (Lebreton et al., 1992)). To measure spawning site fidelity to the Grand River, it would be recommended that a walleye only be considered as having returned to the river to spawn if they are detected at DAM receivers between October and June, based on the results of this study. Furthermore, walleye movement should be monitored on receivers at the other known spawning locations in Lake Erie at the same time do determine if walleye from the Grand River are straying to other spawning populations.

Both sexes of the Grand River walleye population have been found by previous authors to remain relatively close to the Grand River (30-50 km along the north shore west of the river mouth (Matley et al., 2020); see also Figure A6.1Figure A6.2). They also select depth ranges <13 m throughout the year, which is unique compared to other eastern basin and western basin populations, which select depths of >13 m during the summer and often involve significant migrations (Matley et al., 2020). However, despite their local range, 57%

of fish released in 2015, 2016 and 2017 were not detected again in the Grand River during any subsequent year. Nearly equal numbers of male to female fish and fish released above or below Dunnville were not detected in the river during another year subsequent to their initial tagging year. It is unknown at this point why Grand River walleye may not be returning to spawn. Factors could include mortality events, emigration, skipping of spawning seasons, or individuals avoiding detection. There were 31 walleye in this study from which tags were returned, likely from angling or other harvesting activities, and one walleye that was detected as having died at a receiver outside of the Grand River. There could have been other fish that died before being able to return to the river to spawn. Emigration to other spawning populations may be unlikely for Grand River walleye due to their local movement range, making encountering other eastern basin spawning aggregations unlikely. Metabolic stress may also discourage walleye from reproducing, leading to skipped reproduction events. Female walleye and lake trout have been found to skip reproductive seasons, which is thought to be due to insufficient lipid reserves acquired during the foraging season (Henderson et al., 1996; Sitar et al., 2014). It may be important to investigate how habitat variables such as water temperature, flow, turbidity, light levels, and food availability impact spawning behavior and success for Grand River walleye.

This study was designed to have receivers act as a gate that would detect when fish pass points on their upstream and downstream migratory route in the river; however, several abiotic and biotic factors can impact the probability of detecting a fish on a receiver through space and time (Binder et al., 2016; Hayden et al., 2016; Kessel et al., 2014). If the detection probability of receivers is less than one, Grand River walleye may be able to avoid detection in the river, which may bias the analyses of fish movement. Range testing of the Grand River receiver array should be completed to increase the robustness of the conclusions of this study. Potential variation in detection probability among receivers, especially those in the more upstream heterogeneous river stretches, and over time, especially during high flow events, present a key limitation to this study. Analysis of time-ordered pairs of detections that represent movement can be done to identify points where individuals skip receivers when migrating up or downstream. For example, if receivers truly act as gates, then a walleye should not be able to be detected at RES-4 followed by RIF-12 without being detected at RES-11 in between. The relative variation in detection range can be further quantified through range testing procedures where detection efficiency at various distances are determined (Brownscombe et al., 2020; Kessel et al., 2014).

The confirmation of movement of Grand River walleye toward and into the river segment above the Dunnville Dam with suspected spawning habitat during the spawning season has important implications for the management of the Grand River walleye population. The Grand River walleye spawning population has relatively small year-class recruitment compared to other eastern basin populations (Walleye Task Group, 2020). Knowing that walleye in spawning condition will make the additional 25-40 km migration towards more suitable spawning habitat when given the opportunity should encourage action to improve river connectivity for walleye movement. The river segment between Cayuga and Caledonia should be recognized as critically important habitat for Grand River walleye and accessibility improved. Actions like creating a functional fishway or removing the Dunnville Dam would allow for greater access of walleye to spawning habitat and potentially lead to an increase in successful reproduction and production of larval walleye (potential recruitment). Future work should aim to verify spawning activity in the riffle river segment between Dunnville and Caledonia, which can potentially be done by deploying egg matts in locations where suitable spawning habitat occurs (Bade et al., 2019), although this may be logistically very difficult. It may also be important to determine the movement patterns of immature walleye in the Grand River, both above and below the Dunnville Dam. Advancements in tagging technology allow for small juvenile fish to be tracked using acoustic telemetry methods (Cooke et al., 2013). Identifying factors that impact juvenile walleye movement patterns in the Grand River, including how they might be impacted by the Dunnville Dam, would aid in the effort to increase the health of the Grand River recruit.

Identifying the timing and extent of the Grand River walleye spawning migration between Lake Erie and Grand River spawning habitat has contributed to the understanding of population-specific movement ecology in Lake Erie's eastern basin at a local scale. This information may be useful for fisheries managers when planning harvest rules to avoid the overexploitation of this locally adapted population. Lake Erie walleye managers recognize that the eastern basin walleye fishery is comprised of fish from both eastern and western basin spawning populations and have identified the need to pursue a more integrated approach to walleye assessment and management in the eastern basin (Kayle et al., 2015). It may be especially important to investigate if spring fisheries exploit discrete stocks during critical staging or spawning seasons, which may lead to smaller stocks being overfished.

3 Stable isotope analysis and condition of young-of-the-year walleye (*Sander vitreus*) in Ontario's southern Grand River

Contributions:

This study was designed and implemented by Hillary Quinn-Austin in partnership with Tom MacDougall, Mark Servos, and Hadi Dhiyebi. All data analyses and writing presented in this chapter were completed by Hillary Quinn-Austin, with support from Mark Servos, Rebecca Rooney, and Tom MacDougall. Valuable review comments were provided by Simon Courtenay and Heidi Swanson.

3.1 Introduction

Recruitment success, or year-class strength, of walleye often varies substantially among years in the Great Lakes (Schneider and Leach, 1977; Walleye Task Group, 2020). Interannual variability in walleye recruitment can reflect abiotic and biotic conditions that impact early life stages (eggs, larvae, fry) (Ludsin et al., 2014). Growth and survival of young-of-the-year (YOY) walleye may be impacted by physical factors, such as water temperature (Fielder et al., 2007; Hoxmeier et al., 2006; Roseman et al., 2005; Rutherford et al., 2016), river discharge (Mion et al., 1998; Rutherford et al., 2016), and storm events (Roseman et al., 2001; Zhao et al., 2009), as well as biological factors, such as forage availability (Hoxmeier et al., 2006; Roseman et al., 2005) and predation events (Fielder et al., 2007; Hoxmeier et al., 2006; Roseman et al., 2006), which can vary in importance spatially and temporally. Early life stages of walleye experience ontogenetic diet shifts, from eating zooplankton to benthic invertebrates to prey fish, and consequently change their range of movements as they develop and as they change which forage habitat they select (Hoxmeier et al., 2004; Mathias and Li, 1982; Scott and Crossman, 1973). Many tributaries to the Great Lakes have dams that can act as impediments to juvenile walleye movement among nursery and forage habitats (Chapter 2). The complexity of processes that may impact recruitment success of first year walleye among different river and lake systems can make it difficult to predict population viability or to determine causes of interannual variability, which are important to achieve effective management of the overall population and fishery.

Recruitment from the Grand River, Ontario, walleye population of Lake Erie's eastern basin is considered depressed due to restricted access to spawning habitat by a low head dam located at the town of Dunnville, as shown in Chapter 2, and poor habitat quality in lower river stretches (MacDougall et al., 2007; MacDougall and Ryan, 2012). Factors impacting YOY walleye success during their first growing season may shift as they move through the lower river segments, which have variable habitat characteristics due partly to impacted river connectivity (MacDougall and Ryan, 2012). This population is known to be locally adapted (Matley et al., 2020) and divergent from other Lake Erie walleye populations (Strange and Stepien, 2007), and the Grand River therefore listed as a priority management area by the Lake Erie Committee; improving fish access to spawning habitat and restoring the natural hydrological functions of river and estuary habitats are the main objectives (Markham and Knight, 2017; Ryan et al., 2003).

It is important to understand the habitat use and movement ecology of YOY walleye in the southern Grand River at different growth stages, in order to determine what stressors may be impacting their recruitment success and therefore where to focus habitat rehabilitation or protection. YOY walleye in the southern Grand River are initially separated by their hatch location, being either above or below the Dunnville Dam. Early life stages are then suspected to remain within the Grand River for most of their first growing season due to the limited area of mesotrophic habitat in the nearshore of eastern Lake Erie. YOY walleye are rarely found outside of the Grand River in catch surveys along the north shore of the lake (Walleye Task Group, 2020). During their first growing season in the river, YOY walleye are differentially exposed to three habitat segments between the river mouth and the second dam at Caledonia: (1) the lake-effect segment between the river mouth and the Dunnville Dam (includes the Dunnville Marsh Complex), (2) the channelized reservoir segment upstream of the Dunnville Dam until Cayuga, and (3) the riffle segment between Cayuga and Caledonia where the river shifts to having riffle-pool-run series. It is unknown how YOY walleye utilise these segments and if variations in abiotic or biotic stressors among segments may impact YOY walleye health or survival differently.

The objective of this study was to determine if stable isotope analysis could be used to distinguish groups of YOY walleye based on the assimilation of isotopically distinct food webs among river segments, and if these differences could eventually be used to trace YOY walleye movement among river segments and over the growing season. Additionally, length, weight, and condition of YOY walleye were measured in order to compare the health of YOY walleye among river segments and over time and catch-per-unit-effort (CPUE) was recorded to compare abundance of YOY walleye among sampling locations. Based on previously documented trends in stable isotope fractionation in lentic and lotic freshwater ecosystems (Finlay, 2001; France, 1995b; Jardine et al., 2003), I hypothesized that stable carbon and nitrogen isotope ratios of YOY walleye would be significantly different among the three river segments. Due to ontogenetic diet shifts that occur for YOY walleye (Hoxmeier et al., 2006; Mathias and Li, 1982), I hypothesized that there may be significant differences in stable nitrogen isotope ratios of YOY walleye sampled over the course of the growing season. Lastly, possible variation in abiotic and biotic factors among river segments may impact YOY walleye growth and condition, so I hypothesized that there may be significant differences in condition of YOY walleye spatially and temporally over the growing season in the river.

3.2 Methods

3.2.1 Field Sampling

To compare stable carbon and nitrogen stable isotope ratios in YOY walleye among ecologically distinct areas in the southern Grand River, YOY walleye were sampled from five different locations in September of 2018, and in June, July, and September of 2019. YOY walleye were sampled using boat-mounted electrofishing from four sampling locations: the Riffle Transition site (4 continuous 1 km transects downstream from Cayuga), the Reservoir site (4 continuous 1 km transects upstream from the Dunnville Dam), the Below Dam site (3 continuous 1 km transects downstream of the Dunnville Dam), and the River Mouth site (4 continuous 1 km transects upstream from the river mouth at Port Maitland) (Figure 3.1), each with varying habitat characteristics at each sampling location (Table 3.1) (See Table B3.1 in appendices for geographic coordinates of transects). Transects followed the nearshore of the river channel at depths between 0.5-1 m. Effort was taken to sample each transect with similar effort (around 1000 shocking seconds) in order to facilitate comparisons of CPUE among sites. The fifth Riffle sampling location was located at the town of York in the riffle river segment, where seine netting and backpack electrofishing methods were used to sample walleye due to shallow water depths (Figure 3.1). Fish sampling occurred at night (from dusk onward) to coincide with when walleye migrate to near-shore areas to forage. To compare seasonal differences in walleye stable isotope signatures, walleye sampling was conducted at the riffle, riffle transition, and reservoir sampling sites in June, July, and early September in 2019. YOY walleye were kept in aerated coolers while on the electrofishing boat and before being processed on shore on the same day as sampling. Walleye were euthanized through cervical dislocation following methods outlined in University of Waterloo Animal Utilization Project Protocol number 40318 approved by the University of Waterloo Animal Care Committee. Walleye fork length (cm) and weight (g) were recorded before muscle tissue samples were collected for stable isotope analysis. All samples were stored on ice before being transferred to a -20°C freezer pending analysis.

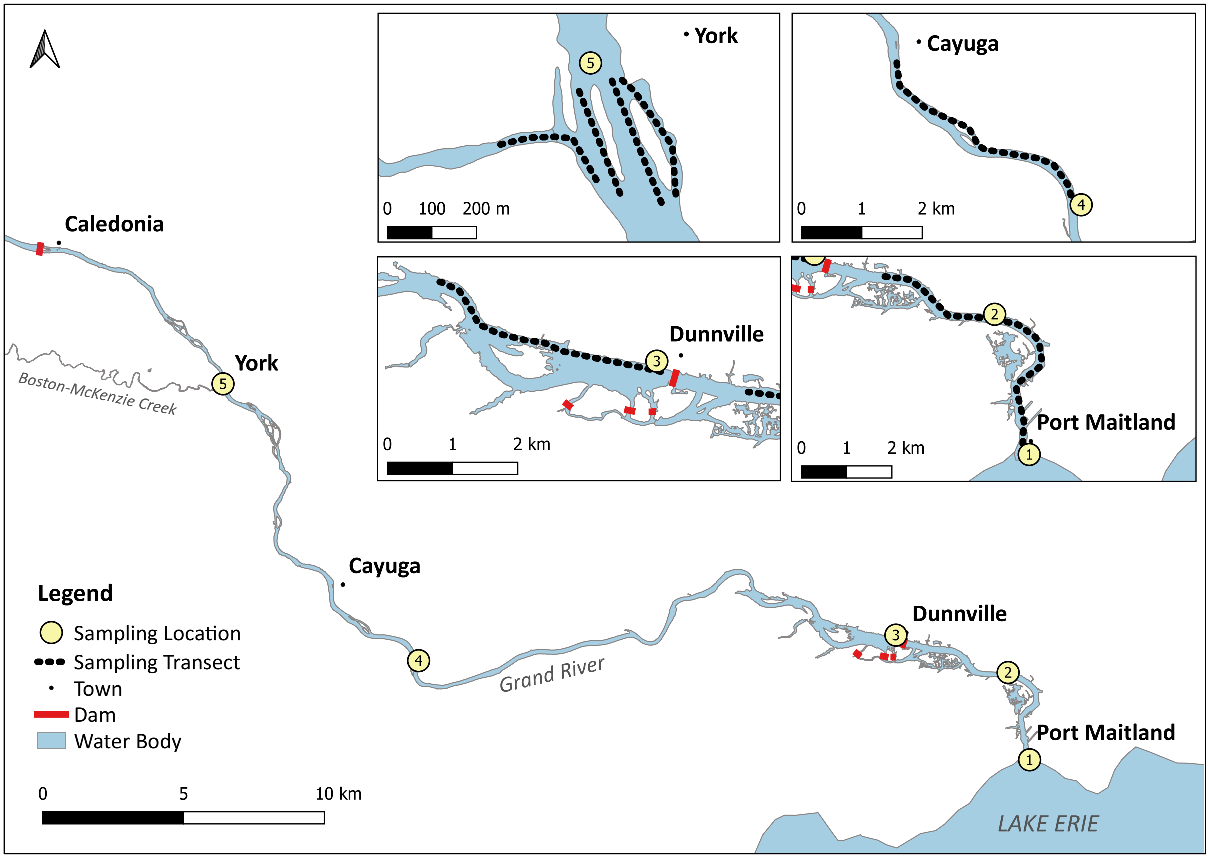

Figure 3.1: Five sampling locations (numbers 1 to 5 refer to the River Mouth, Below Dam, Reservoir, Riffle Transition and Riffle sampling locations, respectively) for young-of-the-year walleye in the southern Grand River, Ontario. Merged sampling transects are indicated by black dashed lines. Towns are indicated by black dots, and dams are indicated by red lines. GIS data was provided by the Ontario Ministry of Natural Resources and Forestry and this map was made in QGIS.

Table 3.1: General habitat characteristics of each sampling location (see Figure 3.1), including characteristics of the main channel, the nearshore littoral zone, and the shoreline or channel boundary.

Site number	**Site name**	**Main channel**	**Nearshore littoral zone**	**Shoreline/channel boundary**
1	River Mouth	- Depth: 5-10 m - High wave action	- Low to no submerged or emergent macrophytes - Rocky or sandy substrate	Mix of rocky, hardened, and mixed vegetation shoreline; transitioned to outer boundary of marsh moving upstream – thick stands of reeds
2	Below Dam	- Depth: 3-5 m - Wave action from Lake Erie dissipated by marsh complex	- Low to no submerged or emergent macrophytes - Sandy or silty substrate - Some submerged logs	Outer boundary of marsh – thick stands of reeds
3	Reservoir	- Depth: 0.5-2 m - Overall shallow with low current velocity	- Low to medium submerged or emergent macrophytes - Silty substrate - Some submerged logs	Mix of rocky, hardened with docks, and mixed vegetation shoreline
4	Riffle Transition	- Depth: 2-4 m - Medium current velocity - Some islands exist that create sheltered channels	- Medium to high submerged and/or emergent macrophytes - Sandy to silty substrate - Many submerged logs	Mostly mixed vegetation; some hardened shoreline with docks

5	Riffle	- Depth: 1-2 m - Mix of riffles and pools with variable current velocities - Islands split river into smaller channels	- Medium to high submerged macrophytes - Rocky to sandy substrate - Some submerged logs	Mixed vegetation shoreline

3.2.2 Laboratory methods

A skinless sample of dorsal white muscle tissue (approximately 5 g wet weight) was removed from YOY walleye for stable isotope analysis. Muscle tissue was rinsed with deionized water before being dried in ovens at 60°C and then ground into homogenous samples using a ball-mill-grinder. An approximately 0.4 mg subsample of dried and ground walleye tissue was weighed into a tin cup to be dual analysed for $\delta^{13}C$ and $\delta^{15}N$ at the Environmental Isotope Laboratory on the University of Waterloo campus. Samples were analysed for ^{13}C and ^{15}N isotope measurements through combustion conversion to gas using a 4010 Elemental Analyzer (Costech Instruments, Italy) coupled to a Delta Plus XL (Thermo-Finnigan, Germany) continuous flow isotope ratio mass spectrometer. Values were reported in delta (δ) notation and calculated as: $\delta^{13}C$ and $\delta^{15}N$ (‰) = $[(R_{sample}/R_{standard}) - 1] \times 1000$, where R is either $^{13}C/^{12}C$ or $^{15}N/^{14}N$ and the standards were Vienna Pee Dee Belemnite and Atmospheric Air for $\delta^{13}C$ and $\delta^{15}N$, respectively. Data quality control reported an error of 0.2‰ $\delta^{13}C$ and 0.3‰ $\delta^{15}N$.

3.2.3 Data Analyses

All statistical analyses were completed using R software version 3.6.2 (R Core Team, 2020), with a significance threshold of alpha = 0.05. All parametric analyses of variance were tested for assumptions of a normal distribution and homogeneity of variance; otherwise permutation models were used.

Catch-per-unit-effort (CPUE) was estimated for each 1 km transect for each sampling location, with catch being the number of YOY walleye caught and effort being 1000 shocking seconds. For transects that were not shocked for exactly 1000 s, the number of fish caught was scaled to per 1000 s using the following equation: CPUE = $1000N/E$, where N is the number of YOY walleye caught and E is the original recorded shocking seconds.

A one-way ANOVA was used to test if mean $\delta^{15}N$ of YOY walleye differed significantly among the five sampling locations, with post-hoc Tukey HSD pairwise comparisons were also performed. Because assumptions of a parametric test could not be met for $\delta^{13}C$, a permutated one-way ANOVA (n=5000 permutations) was used to test if $\delta^{13}C$ varied significantly among sampling locations; again, a post-hoc Tukey HSD test was used to elucidate significant pairwise comparisons.

Log-transformed mean length and weight of YOY walleye caught at similar times were compared among sampling locations using one-way ANOVAs, with post-hoc Tukey HSD pairwise comparisons. A linear regression was performed to determine the YOY walleye length-weight relationship for the southern Grand River population. Condition factor (K) was calculated for YOY walleye using the equation $K = 100(W/L^3)$, where W is total weight in grams, L is length in centimeters. A permutation one-way ANOVA (n=5000 permutations) was then used to determine if YOY walleye condition was significantly different among sampling locations in the river segments, and a post-hoc Tukey's HSD analysis was performed for pairwise comparisons.

3.3 Results

A total of 144 YOY walleye were sampled for fork length and weight from the southern Grand River in September 2018, 134 of which were kept for stable isotope analysis (Table 3.2). Sampling was conducted at three time periods in 2019; however, no YOY walleye were found in June and July, and a total of 14 were found from the Below Dam and River Mouth sampling locations in September (Table 3.2). See the appendices for the number of YOY walleye caught, broken down by transect with associated summary statistics in 2018 (Table B1.1) and 2019 (Table B1.2).

Table 3.2: Number of YOY walleye sampled for length, weight, and stable isotope analysis from five sampling locations (Riffle, Riffle Transition, Reservoir, Below Dam, and River Mouth) in the southern Grand River in September 2018 and in June, July, and September 2019. Sampling for YOY walleye was not completed at the Below Dam and River Mouth sampling locations in June and July 2019.

Sampling Time	**Riffle**	**Riffle Transition**	**Reservoir**	**Below Dam**	**River Mouth**
Sept. 2018	0	31	13	54 (29 for SIA)	46 (41 for SIA)
June 2019	0	0	0	n/a	n/a
July 2019	0	0	0	n/a	n/a

Sept. 2019	0	0	0	4	10

Median CPUE was higher in 2018 than in 2019 when CPUE was compared between years at the same sampling locations; 7 n/1000 s, 2 n/1000 s, 12 n/1000 s, and 10 n/1000 s at the Riffle Transition (n=4), Reservoir (n=4), Below Dam (n=3), and River mouth (n=4) sampling locations, respectively, compared to 0 n/1000 s, 0 n/1000 s, 1 n/1000 s, and 2 n/1000 s in 2019 (Figure 3.2). The Below Dam and River Mouth sampling locations had higher median CPUE than the Riffle Transition and Reservoir sampling locations in both years (Figure 3.2). In 2018, CPUE from the third 1 km transect at the Below Dam sampling location was 29 n/1000 s; nearly three times larger than the CPUE at the first two transects at that location (Figure 3.2).

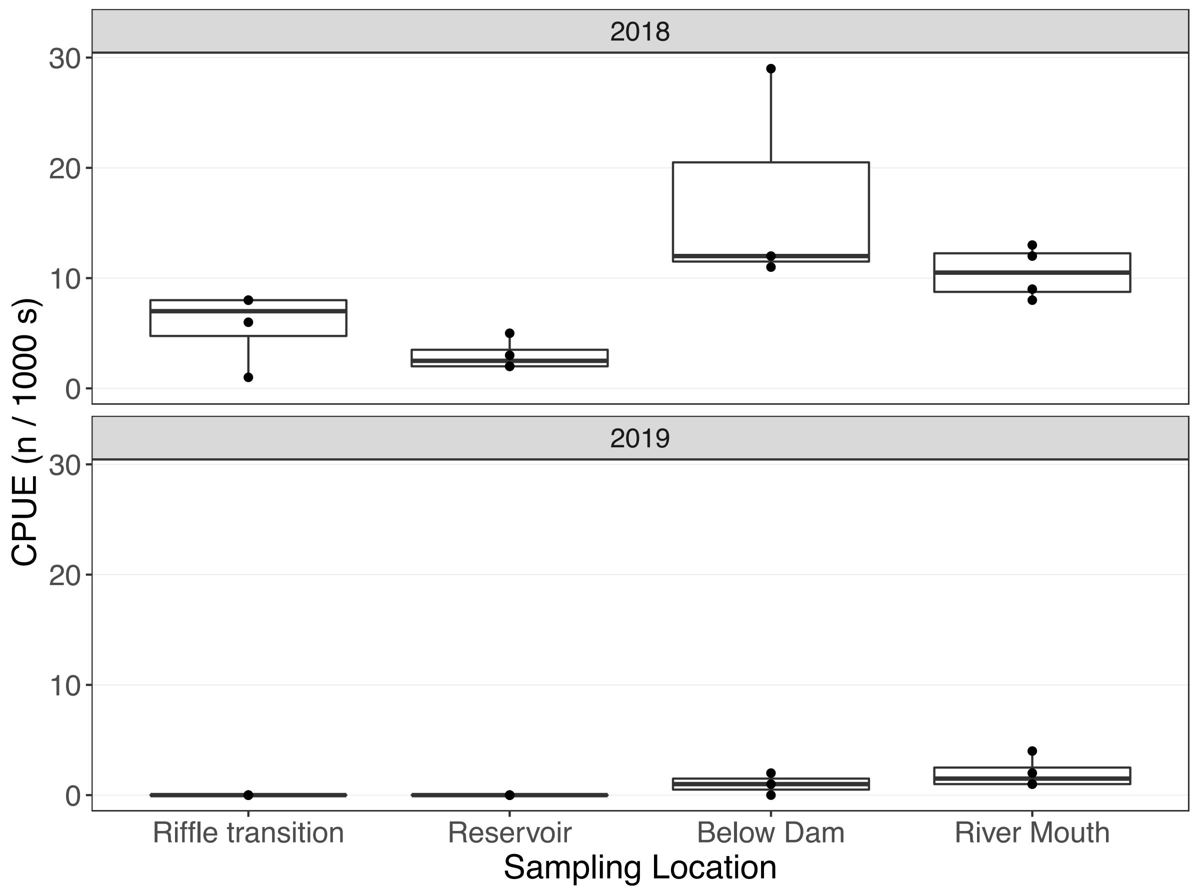

Figure 3.2: CPUE (n/1000 s) of YOY walleye in September of 2018 and 2019 at four sampling locations in the southern Grand River; Riffle transition (n=4), Reservoir (n=3), Below Dam (n=3), and River Mouth (n=4). Each sampling unit is a 1 km transect of 1000 s of boat-mounted electrofishing.

3.3.1 Stable isotope analysis

The mean (± standard error) stable nitrogen isotope ratios (δ15N) isotopic compositions of YOY walleye at the Riffle Transition, Reservoir, Below Dam, and River Mouth sampling locations, respectively, were 18.4‰ ± 0.1, 19.4‰ ± 0.1, 18.9‰ ± 0.1, and 18.6‰ ± 0.1. There was a significant difference in $\delta^{15}N$ of YOY walleye among four sampling locations in the southern Grand River (ANOVA: $F_{3,110} = 22.6$, $p < 0.0001$) (Figure 3.3; Figure B2.1 for model residuals). A Tukey's post hoc test revealed that all pairwise comparisons of $\delta^{15}N$ of YOY walleye among sampling locations were significantly different ($p < 0.05$), except for between the Riffle Transition and River Mouth locations ($p = 0.34$) (Figure 3.3).

The mean (± standard error) stable carbon ($\delta^{13}C$) isotopic compositions of YOY walleye at the Riffle Transition, Reservoir, Below Dam, and River Mouth sampling locations, respectively, were -26.2 ± 0.1, -27.2 ± 0.2, -28.3 ± 0.1, and -27.9 ± 0.1. There was a significant difference in $\delta^{13}C$ among the four sampling locations in the southern Grand River (Permutation ANOVA: $F_{3,110} = 87.2$, $p < 0.0001$) (Figure 3.3; Figure B2.2 for model residuals). Tukey's pairwise comparisons indicated that $\delta^{13}C$ was significantly different among all sampling locations ($p < 0.05$) (Figure 3.3).

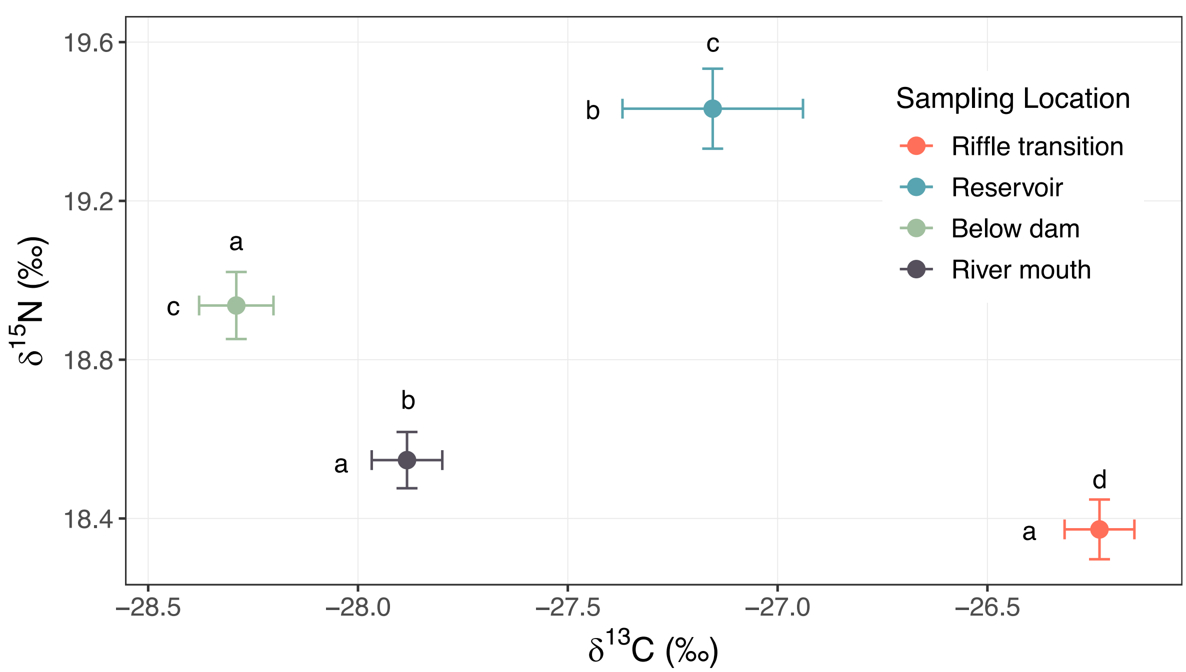

Figure 3.3: Mean (± standard error) stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes from YOY walleye among four sampling locations (Riffle Transition, Reservoir, Below Dam, and River Mouth) in the southern Grand River in September of 2018.

3.3.2 Length, weight, and condition

Log transformed length (ANOVA: $F_{3,140} = 12.1$, $p < 0.0001$) and weight (ANOVA: $F(3,140) = 19.9$, $p < 0.000$) of YOY walleye were both significantly different among sampling locations (Figure 3.4; Figure B2.3 and Figure B2.4 for model residuals). Tukey pairwise comparisons indicated that log length and log weight of YOY walleye sampled from the River Mouth were significantly different than those sampled from the Below Dam ($p < 0.0001$) and the Riffle Transition locations ($p < 0.0001$), and that log length and log weight of YOY walleye at the Reservoir were significantly different from those sampled at the Riffle

Transition ($p < 0.05$) (Figure 3.4).

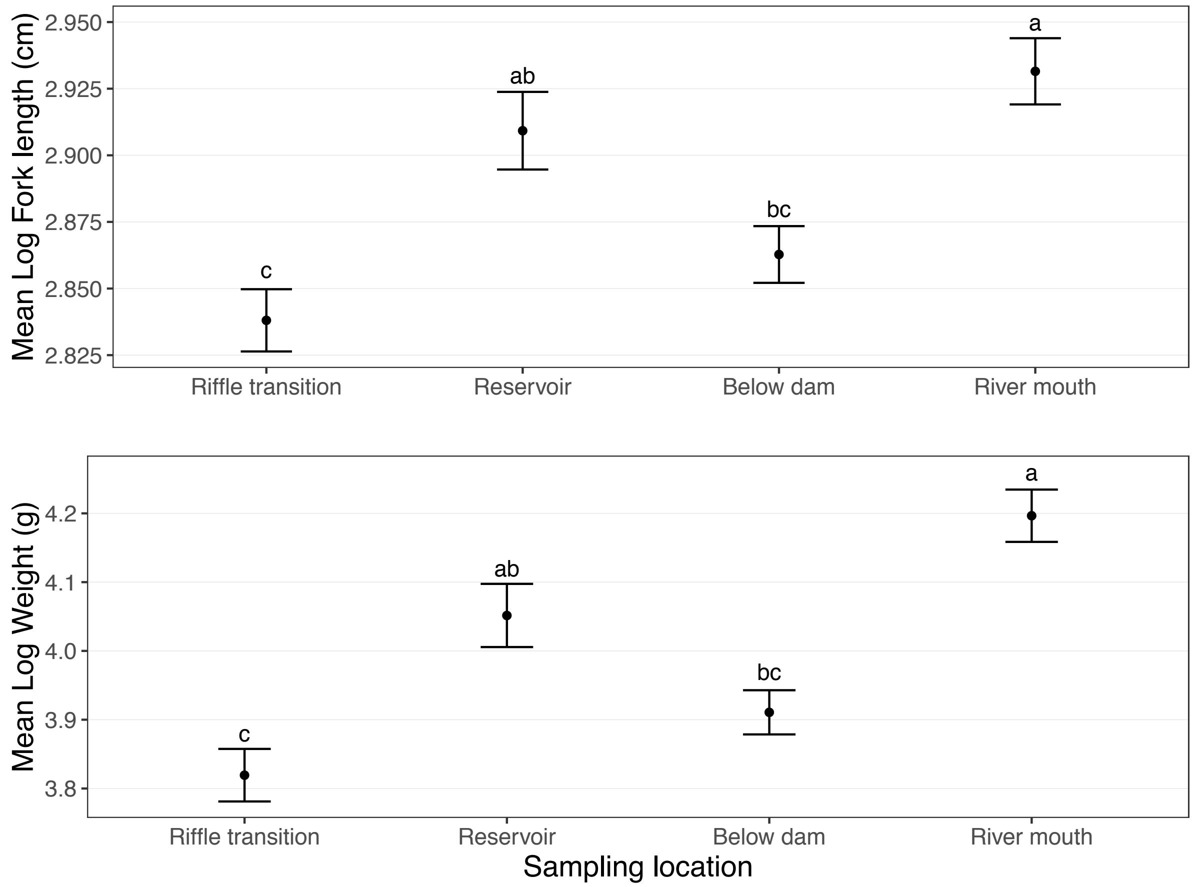

Figure 3.4: Mean (± standard error) of log weight (g) and log fork length (cm) of YOY walleye among sampling locations (Riffle Transition, Reservoir, Below Dam, and River Mouth) in the southern Grand River.

A linear regression of the length-weight relationship with log transformations indicated that fork length had a significant effect on weight ($F_{1,142} = 2112$, $p < 0.0001$) (Figure 3.5; Figure B2.6 for model residuals). Log weight is equal to -5.2 + 3.2*(Log length) in grams, when length is measured in centimeters, and length explains 94% of the variability in weight (adjusted $R^2 = 0.94$), with one outlier. The regression coefficient of 3.2 from the length-weight log-log relationship of YOY walleye indicates near isometric growth for this population.

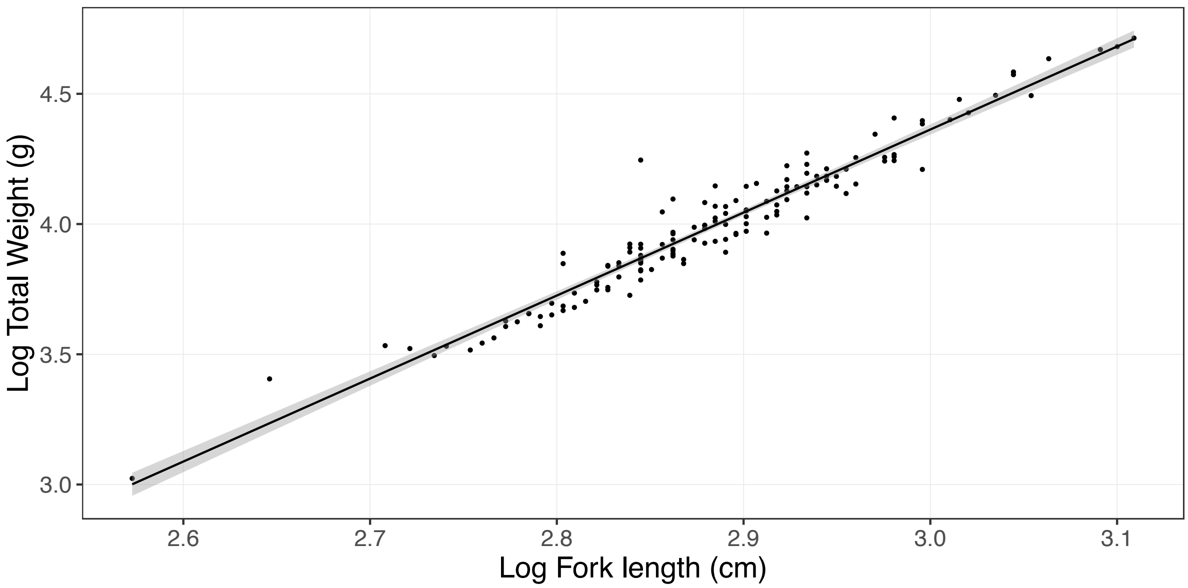

Figure 3.5: Log transformed total weight (g) as a function of log transformed fork length (cm) of YOY walleye from all sampling locations in the southern Grand River, caught in September 2018. The 95% CI is shown in grey.

Condition factor was found to be significantly different among sampling locations in the southern Grand River (permutation ANOVA: $F_{3,140} = 19.4$, $p < 0.0001$), with Tukey HSD post hoc pairwise comparisons revealing that the River Mouth was significantly different than Below Dam ($p < 0.0001$), Reservoir ($p < 0.0001$) and Riffle Transition ($p < 0.0001$) sampling locations (Figure 3.6; Figure B2.5 for model residuals).

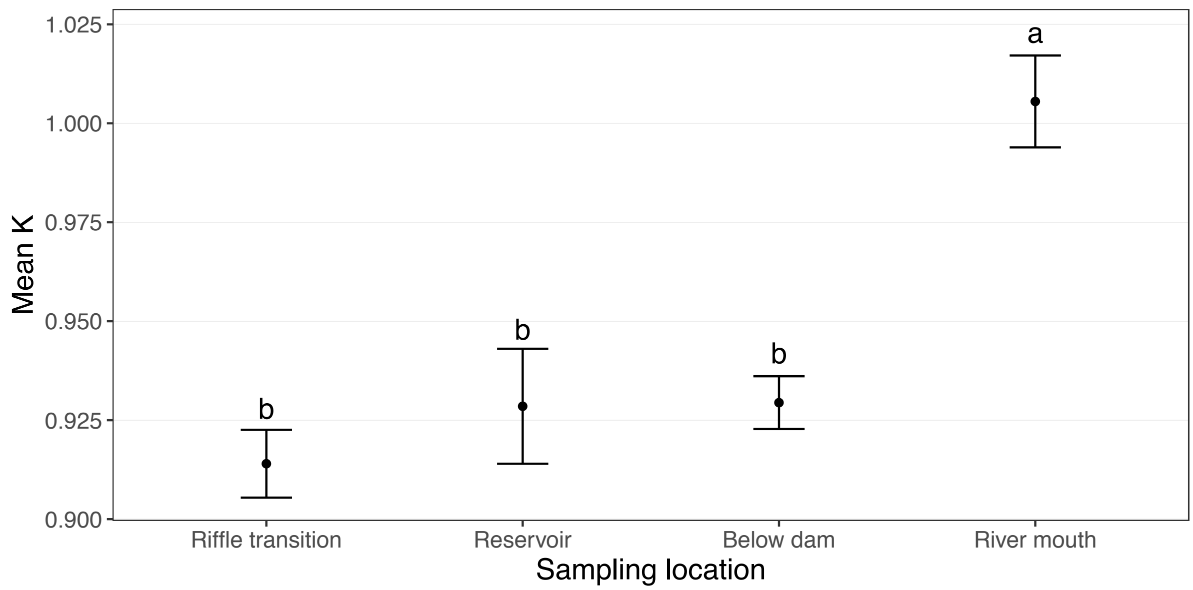

Figure 3.6: Mean (± standard error) of condition factor (K) for YOY walleye among sampling locations (Riffle Transition, Reservoir, Below Dam, and River Mouth) in the southern Grand River.

3.4 Discussion

It is important to understand the spatial and temporal movement of YOY walleye in the southern Grand River to determine where to focus habitat rehabilitation and to understand variability in recruitment success. In this study, I sought to identify the movement of YOY walleye among river segments of the southern Grand River, and as they experience ontogenetic shifts in feeding and habitat selection using shifts in walleye stable carbon and nitrogen isotope composition as evidence. In addition, I sought to compare the health of YOY walleye among river segments using a traditional measurement of condition and to determine if there were variations in YOY walleye abundance among years and seasons. The results of this study revealed that the condition of YOY walleye was higher at the river mouth compared to more upstream locations, and the abundance of YOY walleye (measured with CPUE) was greater in 2018 compared to 2019. Stable carbon and nitrogen isotope signatures of YOY walleye sampled in the fall of 2018 showed significant differences among sampling locations, which may be due to changing environmental conditions moving downstream and relative to the dam as well as changes in food web structure. However, although statistically significant, without knowing the stable isotope composition of the base of the food web, it is not possible to infer what mechanisms cause these differences and whether they indicate YOY walleye movement. Interpretation of both the carbon and nitrogen stable isotope results would be aided by having a representation of the trophic baseline, but sampling of primary consumers was not successful in 2018 and was not completed in 2019 due to my inability to capture YOY walleye.

Differences in condition of YOY walleye among sampling locations sampled in fall of 2018 indicate that individuals from the river mouth are heavier-at-length compared to those with the same length from more upstream locations. The mechanisms explaining this difference are unknown but may be due to changes in physical or biological factors impacting heath, or fatness, among river segments. It is also possible that YOY walleye of greater condition move towards the river mouth at a different rate than those of lower condition. Factors such as water temperature, turbidity, river discharge, prey availability, and predation can impact the health of early walleye life stages, similar to species like yellow perch and lake whitefish in the Great Lakes (reviewed in Ludsin et al., 2014). It is possible that variations in water temperature, prey availability, and/or predator abundance among segments in the Grand River explain the observed differences in size and growth of YOY walleye in this study (e.g. abundance of preferred forage fish like gizzard shad below the Dunnville Dam and increases in centrarchid predators moving upriver (MacDougall and Ryan, 2012)). Few studies have investigated how these factors impact early life stages of walleye in Lake Erie tributaries; most studies have focused on mechanisms impacting growth for YOY walleye on reef spawning populations in the western basin of Lake Erie (Roseman et al., 2005, 2001; Zhao et al., 2009), or for walleye populations in smaller lakes, reservoirs, and pond experiments (Fox, 1989; Hoxmeier et al., 2006, 2004; Hoyle et al., 2017; Johnston and Mathias, 1994). A study on YOY walleye in a tributary of Lake Michigan identified river temperature and discharge as the primary controls on growth and survival of egg and larval life stages (Rutherford et al., 2016).

Although sampling was repeated over three occasions in 2019, CPUE was very low compared to 2018, which may be due to environmental conditions that limited sampling success (high water levels below the dam in 2019), a possibly small spawning aggregation of mature walleye, or low survival of egg and larval stages of walleye during spring. Studies on early life stages of walleye in the Great Lakes indicate that spring storm events and/or high river discharge can cause direct mortality of eggs and larvae (Mion et al., 1998; Roseman et al., 2001), and that slow spring warming rates increase the period for potential egg loss by predation (Roseman et al., 2006). While the condition and success of adult spawning walleye can impact recruitment success, biotic and abiotic variables that impact early life stage survival and growth can have a large influence on interannual variation in year-class, especially for highly fecund species with little parental care such as walleye (Ludsin et al., 2014). Recruitment of western basin YOY walleye in 2019 was the second highest on record for a 31 year period of Ontario and Ohio bottom trawl surveys, with 2018 having the highest recruitment on record (Walleye Task Group, 2020). This indicates that mechanisms controlling year-class strength of walleye may vary between reef and riverine spawning locations, or between basins. In future, it would be beneficial to investigate how annual variation in river discharge and water warming rates impact YOY walleye recruitment for riverine spawning populations.

Stable nitrogen isotope ratios were significantly different among sampling locations in the southern Grand River and were highly enriched (mean $\delta 15N$ of 18.4 ± 0.1‰ to 19.4 ± 0.1‰) at all sites. These results likely indicate a piscivorous diet of YOY walleye across river segments (Jardine et al., 2003), but without the stable isotope ratios of the trophic baseline at each sample location, it is difficult to interpret why there are significant differences among sampling locations. The highly enriched stable nitrogen isotope ratios of YOY walleye may also indicate that the baseline is also highly enriched, which can be expected in a watershed like the Grand River that is greatly impacted by agriculture. Walleye begin to incorporate fish into their diet at a minimum of 2-3 cm and shift to consuming primarily fish once reaching 10 cm (Galarowicz et al., 2006; Mathias and Li, 1982). The YOY walleye analyzed were all >10 cm, so were likely all selecting fish as prey. The forage fish available for YOY walleye among river segments have been found to change in abundance and diversity, with clupeid forage fish being abundant in the lake effect and reservoir segments, but absent from the riffle segment, and spiny-rayed and cyprinid forage fish increasing in abundance in the riffle segment (MacDougall and Ryan, 2012). It is possible that the composition of forage fish consumed by YOY walleye differs significantly among sampling locations and may be reflected in stable isotope ratios, but it is not possible to confirm without the trophic baseline.

YOY walleye sampled had mean stable carbon isotope signatures that ranged from -28.3 ± 0.1‰ to -26.2 ± 0.1‰, with significant differences in $\delta^{13}C$ among all sampling locations. The YOY walleye sampled from below the dam had more depleted stable carbon isotope ratios than those from the reservoir and riffle segments, which may be because $\delta^{13}C$ is negatively related to water velocity, especially in productive rivers (Finlay et al., 1999), and water turbulence is likely higher at the river mouth due to wave action from Lake Erie compared to the shallow and calmer water of the reservoir and riffle transition sampling locations. The more enriched stable carbon isotope ratios of YOY walleye sampled from the reservoir and riffle transition segments may also be because of high levels of primary production (which can lead to carbon limitation (Finlay, 2001)) that likely occur in these shallow, warm, and productive river segments. However, it may be difficult to determine if YOY walleye experienced a diet shift when moving among river segments or as they grow because of the transitional period of ~56 and ~52 days for $\delta^{13}C$ and $\delta^{15}N$ 95% isotopic turnover, respectively, in YOY walleye muscle tissue during which tissue is not at equilibrium with diet (Schumann et al., 2018). Once again, it is difficult to confirm the mechanisms driving changes in stable carbon isotope ratios among river segments without a representation of the trophic baseline.

Due to unsuccessful sampling across all months in 2019, it is still unknown whether there are temporal changes in stable isotopic signature across seasons; however, this is likely the case due to known ontogenetic habitat and diet shifts for YOY walleye (e.g. Galarowicz et al., 2006). Sampling of YOY walleye in the riffle segment was unsuccessful during all five sampling attempts, which may be due to limitations of sampling gear or because YOY walleye are simply not found in this part of the river during the sampling period of this study. However, during initial site exploration in July of 2018, one single YOY walleye was captured using a seine net at the riffle sampling location (just downstream from the mouth of Boston-McKenzie Creek), indicating that there may be some YOY walleye in the area during summer months. For future studies, it may be necessary to explore other methods of sampling YOY walleye for this segment of the river, such as fyke nets or drift nets. A considerably smaller area was covered during sampling at the riffle location compared to other locations due to limitations of using seine nets and backpack electrofishing compared to boat-mounted electrofishing.

Using stable isotopes to track YOY walleye in the southern Grand River may be complicated due to difficulty in sampling and the complex nature of nutrient cycling in rivers and estuary zones. Biotelemetry, a form of electronic tagging technology, is another method that can be used for tracking juvenile fish. Once animals have been tagged, their movements can be tracked as they transmit information between receivers and transmitters.

Advancements in technology have allowed for the use of biotelemetry on small juvenile fishes by reducing tag size, including small radio tags, acoustic tags and passive integrated transponder (PIT) tags, which has led to an increasing number of telemetry based publications on juvenile fish movement patterns (Cooke et al., 2013). There have been telemetry-based movement studies on important juvenile fisheries species like Atlantic salmon (*Salmo salar*) and sockeye salmon (*Oncorhynchus nerka*), both stocked and wild, within rivers and on their migration to catchments (Clark et al., 2016; Larocque et al., 2020), as well as studies on juvenile at risk species like Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) (Whitmore and Litvak, 2018). A study on juvenile Atlantic salmon movement indicated the benefits of using telemetry in combination with stable isotope analysis, where PIT tags were used in combination with stable isotope analysis to distinguish movements related to foraging versus seeking temperature refugia between a tributary and a mainstem river (Cunjak et al., 2005). Using multiple technologies can help support interpretation of results from either method by filling in gaps where limitations arise. Future studies could potentially use biotelemetry to track YOY walleye movement in the southern Grand River, and to determine how the Dunnville Dam may act as an impediment to YOY walleye migration to Lake Erie. If YOY walleye could be caught and tagged both above and below the Dunnville Dam, telemetry methods could be used to determine the length of residency above the dam, in various river segments, and in the river compared to the lake, as well as timing of migration out of the river.

Stable isotope analysis is dependent on the assimilation of isotopically distinct signatures among regions of movement so is well suited to comparisons among large spatial scales and over time broad periods (Hobson, 1999). However, in the southern Grand River, discerning differences in stable isotopes composition among potentially highly mobile YOY walleye has proven challenging. Future studies on this population of YOY walleye may require incorporating new sampling methods and could benefit from the addition of biotelemetry methods. The exact location of spawning and how habitat of the upper river is used by YOY walleye remains unknown. It continues to be important to investigate juvenile movement of YOY walleye in tributaries of Lake Erie, especially for eastern basin populations that have small mesotrophic nearshore habitat areas and may be reliant on healthy riverine and estuarine nursery habitats.

4 Conclusion and recommendations

The Grand River walleye population of Lake Erie's eastern basin is a locally adapted riverine spawning population that has a diminished spawning aggregation and annual recruitment due to degraded habitat connectivity and quality, making the population a minor contributor to the eastern basin mixed-stock fishery (MacDougall et al., 2007; Matley et al., 2020; Strange and Stepien, 2007). It is of interest to the Lake Erie Committee of the Great Lakes Fishery Commission to rehabilitate the Grand River walleye population and avoid its overexploitation in order to conserve diversity within the Lake Erie walleye population, which in turn increases the stability and sustainability of the highly valuable walleye fishery (Kayle et al., 2015). Factors that have been identified as likely limiting the success of the Grand River population include inhibited access to suitable spawning habitat (river connectivity), and suboptimal nursery habitat conditions for YOY walleye survival and growth (Markham and Knight, 2017; Ryan et al., 2003). To inform rehabilitations actions that address these stressors, it was first necessary to understand how both mature and immature walleye interact with various habitat types in the Grand River as they move through space and time.

This study used acoustic telemetry methods to monitor the movement of spawning walleye in the Grand River, both above and below the Dunnville Dam (the first barrier to upstream movement) and successfully illustrated the annual spawning migration in and out of the Grand River. Walleye congregate below the Dunnville Dam in Sulphur Creek in March and April to spawn, and when given access beyond the dam, they continue to migrate another

20-40 km towards areas with suspected suitable spawning habitat further upstream. Walleye perform a return migration towards the river mouth and into Lake Erie, usually arriving below the dam in less than a month, and either remain within the river or exit into the lake for the summer foraging season (June to September). This description of walleye spawning movement indicates the potential for increased spawning activity in river reaches above the Dunnville Dam if river connectivity were restored. While constructing a new fishway is an option to allow upstream walleye movement, many fish passages have been found to be ineffective at moving walleye over dams for migration purposes, including the fish passage that was built on the Dunnville Dam (Bunt et al., 2000). Also, the timing of walleye residence and movement on their return migration suggest that the dam may be acting as an impediment to downstream movement. The reservoir segment of the river above Dunnville has been shown to be hyper-eutrophic, with recorded periods of anoxia and temperatures well above the preferred range for walleye (MacDougall and Ryan, 2012). It is possible that the conditions of the reservoir could cause walleye to experience metabolic stress while upstream of the dam on their downstream migration. The removal of the Dunnville Dam would increase river connectivity for both upstream and downstream walleye movement and would likely improve natural hydrological river processes that could improve riverine habitat quality. However, dam removal is an expensive and logistically challenging endeavor that would require the support of the regulatory authorities and the community.

While increased access to spawning habitat is a critical step towards increased year-class strength, survival and growth of early walleye life stages is also necessary. This study was unable to identify YOY walleye movement among river segments of the southern Grand River using stable isotope analysis. Between 2018 and 2019, the ability to catch YOY walleye varied considerably, indicating possible fluctuations in YOY walleye success among years in the river or the environmental conditions that influence capture. In September 2018, YOY walleye were abundant below the Dunnville Dam and where the river transitions from the riffle segment to the reservoir segment at Cayuga. The presence of YOY walleye above the Dunnville Dam in the late summer indicates successful spawning activity in the upper river reaches and that some YOY walleye stay within the southern Grand River during the summer growing season. However, YOY walleye caught near the river mouth were of higher condition than those caught upstream, which may indicate more favorable conditions for growth below Dunnville. Future research on YOY walleye in the Grand River may benefit from the exploration of new and multiple methods of catching and tracking, including biotelemetry. Monitoring the abundance and condition of YOY walleye in the river among years in relation to environmental covariables would also be beneficial in identifying patterns and drivers of year-class strength variability. This information would be useful in informing rehabilitation actions for the Grand River habitat and walleye population, as well as other eastern basin riverine walleye populations.

Determining the location of spawning beds with evidence of spawning activity in the river segment between Cayuga and Caledonia would be beneficial in monitoring larval walleye movement and factors impacting the success of early life stages. The location of spawning beds, from which YOY walleye caught in the river, is unknown including whether or not there is a resident population of walleye in the river stretch between the Dunnville and Caledonia dams that do not migrate to Lake Erie. It may also be possible that larval walleye move downstream in early spring flow events from the river segment between Caledonia and Brantford. Tagging YOY walleye and mature walleye in the segment between Dunnville and Caledonia dams may help to inform how long walleye are resident in this part of the river, and their local movement ecology.

With regards to the management of the eastern basin walleye fishery, this study has indicated that mature walleye congregate in the lower reaches of the Grand River during April and May, and would be vulnerable to harvest pressure in that area during that time. Furthermore, as a recent study by Matley et al. (2020) indicated using the same GLATOS walleye data, Grand River walleye remain within a relatively local range to the river compared to other eastern basin populations. These results suggest that Grand River walleye may not be vulnerable to fishing activity in the >13 m depth area of the eastern basin, where other spawning populations mix during the summer season. Comparing the apparent annual survival and spawning site fidelity of Lake Erie spawning populations using open-population models would further reveal how the Grand River population may be locally adapted and what factors may impact their spawning site fidelity and reproductive success.

References

Ali, M.A., Anctil, M., 1968. Corrélation entre la structure rétinienne et l'habitat chez Stizostedion vitreum vitreum et S . canadense [Correlation between retinal structure and habitat among *Stizostedion v. vitreum* and *S. canadense.*]. J. Fish. Res. Board Canada 25, 2001–2003. https://doi.org/10.1139/f68-178

Bade, A.P., Binder, T.R., Faust, M.D., Vandergoot, C.S., Hartman, T.J., Kraus, R.T., Krueger, C.C., Ludsin, S.A., 2019. Sex-based differences in spawning behavior account for male-biased harvest in Lake Erie walleye (*Sander vitreus*). Can. J. Fish. Aquat. Sci. 76, 2003–2012. https://doi.org/10.1139/cjfas-2018-0339

Bethke, B.J., Vandehey, J.A., Fincel, M.J., Graeb, B.D.S., Porath, M.T., 2012. Walleye trophic position before and after a gizzard shad extirpation. Prairie Nat. 44, 72–78.

Binder, T.R., Holbrook, C.M., Hayden, T.A., Krueger, C.C., 2016. Spatial and temporal variation in positioning probability of acoustic telemetry arrays: Fine-scale variability and complex interactions. Anim. Biotelemetry 4, 1–15. https://doi.org/10.1186/s40317-016-0097-4

Binder, T.R., Riley, S.C., Holbrook, C.M., Hansen, M.J., Bergstedt, R.A., Bronte, C.R., He, J., Krueger, C.C., 2015. Spawning site fidelity of wild and hatchery lake trout (*Salvelinus namaycush*) in northern Lake Huron. Can. J. Fish. Aquat. Sci. 73, 18–34. https://doi.org/10.1139/cjfas-2015-0175

Braekevelt, C.R., McIntyre, D.B., Ward, F.J., 1989. Development of the retinal tapetum lucidum of the walleye (*Stizostedion vitreum vitreum*). Histol. Histopathol. 4, 63–70.

Brooks, J.L., Boston, C., Doka, S., Gorsky, D., Gustavson, K., Hondorp, D., Isermann, D., Midwood, J.D., Pratt, T.C., Rous, A.M., Withers, J.L., Krueger, C.C., Cooke, S.J., 2017. Use of fish telemetry in rehabilitation planning, management, and monitoring in Areas of Concern in the Laurentian Great Lakes. Environ. Manage. 60, 1139–1154. https://doi.org/10.1007/s00267-017-0937-x

Brooks, J.L., Chapman, J.M., Barkley, A.N., Kessel, S.T., Hussey, N.E., Hinch, S.G., Patterson, D.A., Hedges, K.J., Cooke, S.J., Fisk, A.T., Gruber, S.H., Nguyen, V.M., 2019. Biotelemetry informing management: Case studies exploring successful integration of biotelemetry data into fisheries and habitat management. Can. J. Fish. Aquat. Sci. 76. https://doi.org/10.1139/cjfas-2017-0530

Brownscombe, J.W., Griffin, L.P., Chapman, J.M., Morley, D., Acosta, A., Crossin, G.T., Iverson, S.J., Adams, A.J., Cooke, S.J., Danylchuk, A.J., 2020. A practical method to account for variation in detection range in acoustic telemetry arrays to accurately quantify the spatial ecology of aquatic animals. Methods Ecol. Evol. 11, 82–94. https://doi.org/10.1111/2041-210X.13322

Budy, P., Baker, M., Dahle, S.K., 2011. Predicting fish growth potential and identifying water quality constraints: A spatially-explicit bioenergetics approach. Environ. Manage. 48, 691–709. https://doi.org/10.1007/s00267-011-9717-1

Bunt, C.M., Cooke, S.J., Mckinley, R.S., 2000. Assessment of the Dunnville fishway for passage of walleyes from Lake Erie to the Grand River, Ontario. J. Great Lakes Res. 26, 482–488. https://doi.org/10.1016/S0380-1330(00)70709-X

Chellappa, S., Huntingford, F.A., Strang, R.H.C., Thomson, R.Y., 1995. Condition factor and hepatosomatic index as estimates of energy status in male three-spined stickleback. J. Fish Biol. 47, 775–787. https://doi.org/10.1111/j.1095-8649.1995.tb06002.x

Chevalier, J.R., 1973. Cannibalism as a factor in first year survival of walleye in Oneida Lake. Trans. Am. Fish. Soc. 102, 739–744. https://doi.org/10.1577/1548-8659(1973)102<739:CAAFIF>2.0.CO;2

Chow-Fraser, P., 1998. A conceptual ecological model to aid restoration of Cootes Paradise Marsh, a degraded coastal wetland of Lake Ontario, Canada. Wetl. Ecol. Manag. 6, 43–57. https://doi.org/10.1023/A:1008495604739

Clark, T.D., Furey, N.B., Rechisky, E.L., Gale, M.K., Jeffries, K.M., Porter, A.D., Casselman, M.T., Lotto, A.G., Patterson, D.A., Cooke, S.J., Farrell, A.P., Welch, D.W., Hinch, S.G., 2016. Tracking wild sockeye salmon smolts to the ocean reveals distinct regions of nocturnal movement and high mortality. Ecol. Appl. 26, 959–978. https://doi.org/10.1890/15-0632

Cone, R.S., 1989. The need to reconsider the use of condition indices in fishery science. Trans. Am. Fish. Soc. 118, 510–514. https://doi.org/10.1577/1548-8659(1989)118<0511:TNTRTU>2.3.CO;2

Cooke, S.J., Hinch, S.G., Wikelski, M., Andrews, R.D., Kuchel, L.J., Wolcott, T.G., Butler, P.J., 2004. Biotelemetry: a mechanistic approach to ecology. Trends Ecol. Evol. 19, 334–343. https://doi.org/10.1016/j.tree.2004.04.003

Cooke, S.J., Martins, E.G., Struthers, D.P., Gutowsky, L.F.G., Power, M., Doka, S.E., Dettmers, J.M., Crook, D.A., Lucas, M.C., Holbrook, C.M., Krueger, C.C., 2016. A moving target—incorporating knowledge of the spatial ecology of fish into the assessment and management of freshwater fish populations. Environ. Monit. Assess. 188, 239. https://doi.org/10.1007/s10661-016-5228-0

Cooke, S.J., Midwood, J.D., Thiem, J.D., Klimley, P., Lucas, M.C., Thorstad, E.B., Eiler, J., Holbrook, C., Ebner, B.C., 2013. Tracking animals in freshwater with electronic tags: past, present and future. Anim. Biotelemetry 1, 1–19. https://doi.org/10.1186/2050-3385-1-5

Crossin, G.T., Heupel, M.R., Holbrook, C.M., Hussey, N.E., Lowerre-Barbieri, S.K., Nguyen, V.M., Raby, G.D., Cooke, S.J., 2017. Acoustic telemetry and fisheries management. Ecol. Appl. 27, 1031–1049. https://doi.org/10.1002/eap.1533

Cunjak, R.A., Roussel, J.M., Gray, M.A., Dietrich, J.P., Cartwright, D.F., Munkittrick, K.R., Jardine, T.D., 2005. Using stable isotope analysis with telemetry or mark-recapture data to identify fish movement and foraging. Oecologia 144, 636–646. https://doi.org/10.1007/s00442-005-0101-9

DeNiro, M.J., Epstein, S., 1981. Influence of diet on the distribution of nitrogen isotopes in animals. Geochim. Cosmochim. Acta 45, 341–351. https://doi.org/10.1016/0016-7037(78)90199-0

DeNiro, M.J., Epstein, S., 1978. Influence of diet on the distribution of carbon isotopes in animals. Geochim. Cosmochim. Acta 42, 495–506. https://doi.org/10.1016/0016-7037(78)90199-0

Downing, J.A., Cole, J.J., Middelburg, J.J., Striegl, R.G., Duarte, C.M., Kortelainen, P., Prairie, Y.T., Laube, K.A., 2008. Sediment organic carbon burial in agriculturally eutrophic impoundments over the last century. Global Biogeochem. Cycles 22, 1–10. https://doi.org/10.1029/2006GB002854

DuFour, M.R., May, C.J., Roseman, E.F., Ludsin, S.A., Vandergoot, C.S., Pritt, J.J., Fraker, M.E., Davis, J.J., Tyson, J.T., Miner, J.G., Marschall, E.A., Mayer, C.M., 2015. Portfolio theory as a management tool to guide conservation and restoration of multi-stock fish populations. Ecosphere 6, 1–21. https://doi.org/10.1890/ES15-00237.1

Ecologistics, 1982. Study of the Grand River substrate. Internal document prepared for the Ontario Ministry of Natural Resources, Vineland, ON.

Faust, M.D., Vandergoot, C.S., Brenden, T.O., Kraus, R.T., Hartman, T., Krueger, C.C., 2019. Acoustic telemetry as a potential tool for mixed-stock analysis of fishery harvest: A feasibility study using lake erie walleye. Can. J. Fish. Aquat. Sci. 76, 1019–1030. https://doi.org/10.1139/cjfas-2017-0522

Fielder, D.G., Schaeffer, J.S., Thomas, M. V., 2007. Environmental and ecological conditions surrounding the production of large year classes of walleye (*Sander vitreus*) in Saginaw Bay, Lake Huron. J. Great Lakes Res. 33, 118–132. https://doi.org/10.3394/0380-1330(2007)33[118:EAECST]2.0.CO;2

Figge, F., 2004. Bio-folio: Applying portfolio theory to biodiversity. Biodivers. Conserv. https://doi.org/10.1023/B:BIOC.0000011729.93889.34

Finlay, J.C., 2001. Stable-carbon-isotope ratios of river biota: Implications for energy flow in lotic food webs. Ecology 82, 1052–1064. https://doi.org/10.1890/0012-9658(2001)082[1052:SCIROR]2.0.CO;2

Finlay, J.C., Power, M.E., Cabana, G., 1999. Effects of water velocity on algal carbon isotope ratios: Implications for river food web studies. Limnol. Oceanogr. 44, 1198–1203. https://doi.org/10.4319/lo.1999.44.5.1198

Forage Task Group, 2009. Report of the Lake Erie Forage Task Group, Presented to the Standing Technical Committee of the Great Lakes Fishery Commission's Lake Erie Committee.

Forney, J.L., 1974. Interactions between yellow perch abundance, walleye predation, and survival of alternate prey in Oneida Lake, New York. Trans. Am. Fish. Soc. 103, 15–24. https://doi.org/10.1577/1548-8659(1974)103<15:IBYPAW>2.0.CO;2

Fox, M.G., 1989. Effect of prey density and prey size on growh and survival sf juvenile walleye (*Stizastedian vitreum viereurn*). Can. J. Fish. Aquat. Sci. 46, 1323–1328.

France, R.L., 1995a. Differentiation between littoral and pelagic food webs in lakes using stable carbon isotopes. Limnol. Oceanogr. 40, 1310–1313. https://doi.org/10.4319/lo.1995.40.7.1310

France, R.L., 1995b. Carbon-13 enrichment in benthic compared to planktonic algae: foodweb implications. Mar. Ecol. Prog. Ser. 124, 307–312.

Freedman, J.A., Lorson, B.D., Taylor, R.B., Carline, R.F., Stauffer, J.R., 2014. River of the dammed: Longitudinal changes in fish assemblages in response to dams. Hydrobiologia 727, 19–33. https://doi.org/10.1007/s10750-013-1780-6

Froese, R., 2006. Cube law, condition factor and weight-length relationships: History, meta-analysis and recommendations. J. Appl. Ichthyol. 22, 241–253. https://doi.org/10.1111/j.1439-0426.2006.00805.x

Galarowicz, T.L., Adams, J.A., Wahl, D.H., 2006. The influence of prey availability on ontogenetic diet shifts of a juvenile piscivore. Can. J. Fish. Aquat. Sci. 63, 1722–1733. https://doi.org/10.1139/f06-073

Gilbert, J.M., Ryan, P.A., 2007. Southern Grand River wetland report, Ontario Ministry of Natural Resources Lake Erie Management Unit. Port Dover, Ontario.

Gowan, C., Young, M.K., Fausch, K.D., Riley, S.C., 1994. Restricted movement in resident stream salmonids: A paradigm lost? Can. J. Fish. Aquat. Sci. https://doi.org/10.1139/f94-262

GRWMP-Lake Erie Working Group, 2012. A framework for identifying indicators of water resource conditions support of ecological health by water resources in the Grand River-Lake Erie interface.

Hayden, T.A., Binder, T.R., Holbrook, C.M., Vandergoot, C.S., Fielder, D.G., Cooke, S.J., Dettmers, J.M., Krueger, C.C., 2018. Spawning site fidelity and apparent annual survival of walleye (*Sander vitreus*) differ between a Lake Huron and Lake Erie tributary. Ecol. Freshw. Fish 27, 339–349. https://doi.org/10.1111/eff.12350

Hayden, T.A., Holbrook, C.M., Binder, T.R., Dettmers, J.M., Cooke, S.J., Vandergoot, C.S., Krueger, C.C., 2016. Probability of acoustic transmitter detections by receiver lines in Lake Huron: Results of multi-year field tests and simulations. Anim. Biotelemetry 4, 19. https://doi.org/10.1186/s40317-016-0112-9

Hayden, T.A., Holbrook, C.M., Fielder, D.G., Vandergoot, C.S., Bergstedt, R.A., Dettmers, J.M., Krueger, C.C., Cooke, S.J., 2014. Acoustic telemetry reveals large-scale mirgration patterns of walleye in Lake Huron. PLoS One 9, 1–19. https://doi.org/10.1371/journal.pone

Hayden, T.A., Vandergoot, C.S., Fielder, D.G., Cooke, S.J., Dettmers, J.M., Krueger, C.C., 2019. Telemetry reveals limited exchange of walleye between Lake Erie and Lake Huron: Movement of two populations through the Huron-Erie corridor. J. Great Lakes Res. 45, 1241–1250. https://doi.org/10.1016/j.jglr.2019.09.014

Henderson, B.A., Wong, J.L., Nepszy, S.J., 1996. Reproduction of walleye in Lake Erie: Allocation of energy. Can. J. Fish. Aquat. Sci. 53, 127–133. https://doi.org/10.1139/f95-162

Henley, W.F., Patterson, M.A., Neves, R.J., Dennis Lemly, A., 2000. Effects of sedimentation and turbidity on lotic food webs: A concise review for natural resource managers. Rev. Fish. Sci. 8, 125–139. https://doi.org/10.1080/10641260091129198

Heupel, M.R., Semmens, J.M., Hobday, A.J., 2006. Automated acoustic tracking of aquatic animals: scales, design and deployment of listening station arrays. Mar. Freshw. Res. 57, 113. https://doi.org/10.1071/MF05091

Hicks, K.A., Loomer, H.A., Fuzzen, M.L.M., Kleywegt, S., Tetreault, G.R., Mcmaster, M.E., Servos, M.R., 2017. δ15N tracks changes in the assimilation of sewage-derived nutrients into a riverine food web before and after major process alterations at two municipal wastewater treatment plants. Ecol. Indic. 72, 747–758. https://doi.org/10.1016/j.ecolind.2016.09.011

Hilborn, R., Quinn, T.P., Schindler, D.E., Rogers, D.E., 2003. Biocomplexity and fisheries sustainability. Proc. Natl. Acad. Sci. U. S. A. 100, 6564–6568. https://doi.org/10.1073/pnas.1037274100

Hobson, K.A., 1999. Tracing origins and migration of wildlife using stable isotopes: A review. Oecologia 120, 314–326. https://doi.org/10.1007/s004420050865

Hokanson, K.E.F., 1977. Temperature requirements of some percids and adaptations to the seasonal temperature cycle. J. Fish. Res. Board Canada 34, 1524–1550. https://doi.org/10.1139/f77-217

Hoxmeier, R.J.H., Wahl, D.H., Brooks, R.C., Heidinger, R.C., 2006. Growth and survival of age-0 walleye (*Sander vitreus*): Interactions among walleye size, prey availability, predation, and abiotic factors. Can. J. Fish. Aquat. Sci. 63, 2173–2182. https://doi.org/10.1139/F06-087

Hoxmeier, R.J.H., Wahl, D.H., Hooe, M.L., Pierce, C.L., 2004. Growth and survival of larval walleyes in response to prey availability. Trans. Am. Fish. Soc. 133, 45–54. https://doi.org/10.1577/t01-082

Hoyle, J.A., Holden, J.P., Yuille, M.J., 2017. Diet and relative weight in migratory walleye (*Sander vitreus*) of the Bay of Quinte and eastern Lake Ontario, 1992–2015. J. Great Lakes Res. 43, 846–853. https://doi.org/10.1016/j.jglr.2017.01.013

Hussey, N.E., Kessel, S.T., Aarestrup, K., Cooke, S.J., Cowley, P.D., Fisk, A.T., Harcourt, R.G., Holland, K.N., Iverson, S.J., Kocik, J.F., Flemming, J.E.M., Whoriskey, F.G., 2015. Aquatic animal telemetry: A panoramic window into the underwater world. Science (80-.). 348, 1255642. https://doi.org/10.1126/science.1255642

Jardine, T.D., Hadwen, W.L., Hamilton, S.K., Hladyz, S., Mitrovic, S.M., Kidd, K.A., Tsoi, W.Y., Spears, M., Westhorpe, D.P., Fry, V.M., Sheldon, F., Bunn, S.E., 2014. Understanding and overcoming baseline isotopic variability in running waters. River Res. Appl. 30, 155–165. https://doi.org/10.1002/rra.2630

Jardine, T.D., McGeachy, S.A., Paton, C.M., Savoie, M., Cunjak, R.A., 2003. Stable isotopes in aquatic systems: sample preparation, analysis, and interpretation, Fisheries and Aquatic Sciences. Fredericton, NB, Canada.

Johnston, T.A., Mathias, J., 1994. Feeding ecology of walleye, *Stizostedion vitreum*, larvae: Effects of body size, zooplankton abundance, and zooplankton community composition. Can. J. Fish. Aquat. Sci. 51, 2077–2089. https://doi.org/10.1139/f94-210

Jones, R.E., Petrell, R.J., Pauly, D., 1999. Using modified length-weight relationships to assess the condition of fish. Aquac. Eng. 20, 261–276. https://doi.org/10.1016/S0144-8609(99)00020-5

Kayle, K., Oldenburg, K., Murray, C., Francis, J., Markham, J., 2015. Lake Erie Walleye Management Plan 2015-2019 [online]. Available from http://www.glfc.org/pubs/lake_committees/erie/LEC_docs/position_statements/walleye _managment_plan.pdf.

Keeley, J.E., Sandquist, D.R., 1992. Carbon: freshwater plants. Plant. Cell Environ. 15, 1021–1035. https://doi.org/10.1111/j.1365-3040.1992.tb01653.x

Kennedy, B.P., Chamberlain, C.P., Blum, J.D., Nislow, K.H., Folt, C.L., 2005. Comparing naturally occurring stable isotopes of nitrogen, carbon, and strontium as markers for the rearing locations of Atlantic salmon (*Salmo salar*). Can. J. Fish. Aquat. Sci. 62, 48–57. https://doi.org/10.1139/f04-184

Kessel, S.T., Cooke, S.J., Heupel, M.R., Hussey, N.E., Simpfendorfer, C.A., Vagle, S., Fisk, A.T., 2014. A review of detection range testing in aquatic passive acoustic telemetry studies. Rev. Fish Biol. Fish. 24, 199–218. https://doi.org/10.1007/s11160-013-9328-4

Klimley, P.A., Voegeli, F., Beavers, S.C., Le Boeuf, B.J., 1998. Automated listening stations for tagged marine fishes. Mar. Technol. Soc. J. 32, 94.

Landsman, S.J., Nguyen, V.M., Gutowsky, L.F.G., Gobin, J., Cook, K. V, Binder, T.R., Lower, N., McLaughlin, R.L., Cooke, S.J., 2011. Fish movement and migration studies in the Laurentian Great Lakes: Research trends and knowledge gaps. J. Great Lakes Res. 37, 365–379. https://doi.org/10.1016/j.jglr.2011.03.003

Larocque, S.M., Johnson, T.B., Fisk, A.T., 2020. Survival and migration patterns of naturally and hatchery-reared Atlantic salmon (*Salmo salar*) smolts in a Lake Ontario tributary using acoustic telemetry. Freshw. Biol. 00, 1–14. https://doi.org/10.1111/fwb.13467

Lebreton, J.D., Burnham, K.P., Clobert, J., Anderson, D.R., 1992. Modeling survival and testing biological hypotheses using marked animals: a unified approach with case studies. Ecol. Monogr. 62, 67–118. https://doi.org/10.2307/2937171

Ludsin, S.A., De Vanna, K.M., Smith, R.E.H., 2014. Physical-biological coupling and the challenge of understanding fish recruitment in freshwater lakes. Can. J. Fish. Aquat. Sci. 71, 775–794. https://doi.org/10.1139/cjfas-2013-0512

MacDougall, T.M., Ryan, P.A., 2012. An assessment of aquatic habitat in the southern Grand

River, Ontario: Water quality, lower trophic levels, and fish communities. Port Dover, Ontario.

MacDougall, T.M., Wilson, C.C., Richardson, L.M., Lavender, M., Ryan, P.A., 2007. Walleye in the Grand River, Ontario: an overview of rehabilitation efforts, their effectiveness, and implications for eastern Lake Erie fisheries. J. Great Lakes Res. 33, 103–117. https://doi.org/10.3394/0380-1330(2007)33[103:WITGRO]2.0.CO;2

Madenjian, C.P., Hayden, T.A., Peat, T.B., Vandergoot, C.S., Fielder, D.G., Gorman, A.M., Pothoven, S.A., Dettmers, J.M., Cooke, S.J., Zhao, Y., Krueger, C.C., 2018. Temperature regimes, growth, and food consumption for female and male adult walleye in Lake Huron and Lake Erie: a bioenergetics analysis. Can. J. Fish. Aquat. Sci. 75, 1573–1586. https://doi.org/10.1139/cjfas-2017-0280

Manly, B.F., 2006. Randomization, bootstrap and Monte Carlo methods in biology. Vol. 70. CRC press.

Mapes, R.L., Dufour, M.R., Pritt, J.J., Mayer, C.M., 2015. Larval fish assemblage recovery: A reflection of environmental change in a large degraded river. Restor. Ecol. 23, 85–93. https://doi.org/10.1111/rec.12138

Markham, J.L., Knight, R.L., 2017. The state of Lake Erie in 2009 [online]. Available from: http://www.glfc.org/pubs/SpecialPubs/Sp17_01.pdf.

Mathias, J., Li, S., 1982. Feeding habits of Walleye larvae and juveniles: comparative laboratory and field studies. Trans. Am. Fish. Soc. 111, 722–735. https://doi.org/10.1577/1548-8659(1982)111<722

Matley, J.K., Faust, M.D., Raby, G.D., Zhao, Y., Robinson, J., MacDougall, T., Hayden, T.A., Fisk, A.T., Vandergoot, C.S., Krueger, C.C., 2020. Seasonal habitat-use differences among Lake Erie's walleye stocks. J. Great Lakes Res. 46, 609–621. https://doi.org/10.1016/j.jglr.2020.03.014

Minagawa, M., Wada, E., 1984. Stepwise enrichment of 15N along food chains: Further evidence and the relation between δ15N and animal age. Geochim. Cosmochim. Acta 48, 1135–1140. https://doi.org/10.1016/0016-7037(84)90204-7

Mion, J.B., Stein, R.A., Marschall, E.A., 1998. River discharge drives survival of larval walleye. Ecol. Appl. 8, 88–103. https://doi.org/10.1890/1051-0761(1998)008[0088:RDDSOL]2.0.CO;2

Miranda, L.E., Habrat, M.D., Miyazono, S., 2008. Longitudinal gradients along a reservoir cascade. Trans. Am. Fish. Soc. 137, 1851–1865. https://doi.org/10.1577/T07-262.1

Nilsson, C., Berggren, K., 2000. Alterations of riparian ecosystems caused by river regulation. Bioscience 50, 783–792. https://doi.org/10.1641/0006-3568(2000)050[0783:AORECB]2.0.CO;2

Ontario Ministry of Natural Resources (OMNR), 2009. Terms of Reference; ARDS ACC Membership; Guide for submission of animal use protocols; Information resources; Class protocols. Aquatic Research and Development Section, Animal Care Committee. 69p.

Osmond, C.B., Valaane, N., Haslam, S.M., Uotila, P., Roksandic, Z., 1981. Comparisons of δ13C values in leaves of aquatic macrophytes from different habitats in Britain and Finland; some implications for photosynthetic processes in aquatic plants. Oecologia 50, 117–124. https://doi.org/10.1007/BF00378804

Overman, N.C., Parrish, D.L., 2001. Stable isotope composition of walleye: 15N accumulation with age and area-specific differences in δ13C. Can. J. Fish. Aquat. Sci. 58, 1253–1260. https://doi.org/10.1139/cjfas-58-6-1253

Peake, S., McKinley, R.S., Scruton, D.A., 2000. Swimming performance of walleye (*Stizostedion vitreum*). Can. J. Zool. 78, 1686–1690. https://doi.org/10.1139/z00-097

Peat, T.B., Hayden, T.A., Gutowsky, L.F., Vandergoot, C.S., Fielder, D.G., Madenjian, C.P., Murchie, K.J., Dettmers, J.M., Krueger, C.C., Cooke, S.J., 2015. Seasonal thermal ecology of adult walleye (*Sander vitreus*) in Lake Huron and Lake Erie. J. Therm. Biol.

53, 98–106. https://doi.org/10.1016/j.jtherbio.2015.08.009

Peterson, B.J., Fry, B., 1987. Stable isotopes in ecosystem studies. Annu. Rev. Ecol. Syst. 18, 293–320.

Pincock, D.G., 2012. False detections: What they are and how to remove them from detection data (No. DOC-004691 Version 03), Halifax, NS: Vemco Inc.

Pinnegar, J.K., Polunin, N.V.C., 2000. Contributions of stable-isotope data to elucidating food webs of Mediterranean rocky littoral fishes. Oecologia 122, 399–409. https://doi.org/10.1007/s004420050046

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime. Bioscience 47, 769–784. https://doi.org/10.2307/1313099

Post, D.M., 2002. Using stable isotopes to estimate trophic position: models, methods, and assumptions. Ecology 83, 703–718. https://doi.org/10.1890/0012-9658(2002)083[0703:USITET]2.0.CO;2

Power, M.E., Dietrich, W.E., Finlay, J.C., 1996. Dams-downstream aquatic biodiversity: Potential food web consequences of hydrologic and geomorphic change. Environ. Manage. 20, 887–895.

Pritt, J.J., Dufour, M.R., Mayer, C.M., Kocovsky, P.M., Tyson, J.T., Weimer, E.J., Vandergoot, C.S., 2013. Including independent estimates and uncertainty to quantify total abundance of fish migrating in a large river system: walleye (*Sander vitreus*) in the Maumee River, Ohio. Can. J. Fish. Aquat. Sci. 70, 803–814. https://doi.org/10.1139/cjfas-2012-0484

Quist, M.C., Guy, C.S., Stephen, J.L., 2003. Recruitment dynamics of walleyes (*Stizostedion vitreum*) in Kansas reservoirs: generalities with natural systems and effects of a centrarchid predator. Can. J. Fish. Aquat. Sci. 60, 830–839. https://doi.org/10.1139/f03-067

R Core Team, 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Roseman, E.F., Kocovsky, P., Vandergoot, C., 2010. Status of walleye in the Great Lakes: Proceedings of the 2006 Symposium, Technical Report 69. Great Lakes Fishery Commission. U.S. Geological Survey. Ann Arbor, MI.

Roseman, E.F., Taylor, W.W., Hayes, D.B., Jones, A.L., Francis, J.T., 2006. Predation on walleye eggs by fish on reefs in western Lake Erie. J. Great Lakes Res. 32, 415–423. https://doi.org/10.3394/0380-1330(2006)32[415:POWEBF]2.0.CO;2

Roseman, E.F., Taylor, W.W., Hayes, D.B., Knight, R.L., Haas, R.C., 2001. Removal of walleye eggs from reefs in western Lake Erie by a catastrophic storm. Trans. Am. Fish. Soc. 130, 341–346. https://doi.org/10.1577/1548-8659(2001)130<0341:rowefr>2.0.co;2

Roseman, E.F., Taylor, W.W., Hayes, D.B., Tyson, J.T., Haas, R.C., 2005. Spatial patterns emphasize the importance of coastal zones as nursery areas for larval walleye in western Lake Erie. J. Great Lakes Res. 31, 28–44. https://doi.org/10.1016/S0380-1330(05)70288-4

Rosenberg, D.M., Berkes, F., Bodaly, R.A., Hecky, R.E., Kelly, C.A., Rudd, J.W.M., 1997. Large-scale impacts of hydroelectric development. Environ. Rev. 5, 27–54. https://doi.org/10.1139/er-5-1-27

Rutherford, E.S., Allison, J., Ruetz, C.R., Elliott, J.R., Nohner, J.K., DuFour, M.R., O'Neal, R.P., Jude, D.J., Hensler, S.R., 2016. Density and survival of walleye eggs and larvae in a Great Lakes tributary. Trans. Am. Fish. Soc. 145, 563–577. https://doi.org/10.1080/00028487.2016.1145135

Ryan, P.A., Knight, R., MacGregor, R., Towns, G., Hoopes, R., Culligan, W., 2003. Fish-community goals and objectives for Lake Erie, Great Lakes Fisheries Commission Special Publication. 03-02.

Santucci Jr., V.J., Wahl, D.H., 1993. Factors influencing survival and growth of stocked walleye (*Stizostedion vitreum*) in a centrarchid-dominated impoundment. Can. J. Fish. Aquat. Sci. 50, 1548–1558. https://doi.org/10.1139/f93-176

Schindler, D.E., Hilborn, R., Chasco, B., Boatright, C.P., Quinn, T.P., Rogers, L.A., Webster, M.S., 2010. Population diversity and the portfolio effect in an exploited species. Nature 465, 609–612. https://doi.org/10.1038/nature09060

Schneider, J.C., Leach, J.H., 1977. Walleye (*Stizostedion vitreum vitreum*) fluctuations in the Great Lakes and possible causes, 1800–1975. J. Fish. Res. Board Canada 34, 1878–1889. https://doi.org/10.1139/f77-254

Schumann, D.A., Uphoff, C.S., Schoenebeck, C.W., Graeb, K.N.B., 2018. Incorporation of carbon and nitrogen isotopes in age-0 walleye (*Sander vitreus*) tissues following a laboratory diet switch experiment. Can. J. Fish. Aquat. Sci. 75, 497–505. https://doi.org/10.1139/cjfas-2017-0301

Scott, W.B., Crossman, E.J., 1973. Freshwater fishes of Canada. Fisheries Research Board of Canada Bulletin 184.

Sitar, S.P., Jasonowicz, A.J., Murphy, C.A., Goetz, F.W., 2014. Estimates of skipped spawning in Lean and Siscowet Lake Trout in southern Lake Superior: Implications for stock assessment. Trans. Am. Fish. Soc. 143, 660–672. https://doi.org/10.1080/00028487.2014.880745

Stasko, A.B., Pincock, D.G., 1977. Review of underwater biotelemetry, with emphasis on ultrasonic techniques. J. Fish. Res. Board Canada 34, 1261–1285. https://doi.org/10.1139/f77-189

Stepien, C.A., Snyder, M.R., Knight, C.T., 2018. Genetic divergence of nearby walleye spawning groups in central Lake Erie: Implications for management. North Am. J. Fish. Manag. 38, 783–793. https://doi.org/10.1002/nafm.10176

Strange, R.M., Stepien, C.A., 2007. Genetic divergence and connectivity among river and reef spawning groups of walleye (*Sander vitreus vitreus*) in Lake Erie. Can. J. Fish.

Aquat. Sci. 64, 437–448. https://doi.org/10.1139/f07-022

Trebitz, A.S., Brazner, J.C., Brady, V.J., Axler, R., Tanner, D.K., 2007. Turbidity tolerances of Great Lakes coastal wetland fishes. North Am. J. Fish. Manag. 27, 619–633. https://doi.org/10.1577/M05-219.1

Vander Zanden, M.J., Clayton, M.K., Moody, E.K., Solomon, C.T., Weidel, B.C., 2015. Stable isotope turnover and half-life in animal tissues: A literature synthesis. PLoS One 10, 1–16. https://doi.org/10.1371/journal.pone.0116182

Vandergoot, C.S., Murchie, K.J., Cooke, S.J., Dettmers, J.M., Bergstedt, R.A., Fielder, D.G., 2011. Evaluation of two forms of electroanesthesia and carbon dioxide for short-term anesthesia in walleye. North Am. J. Fish. Manag. 31, 914–922. https://doi.org/10.1080/02755947.2011.629717

Wagner, G.N., Cooke, S.J., Brown, R.S., Deters, K.A., 2011. Surgical implantation techniques for electronic tags in fish. Rev. Fish Biol. Fish. 21, 71–81. https://doi.org/10.1007/s11160-010-9191-5

Walleye Task Group, 2020. Report for 2019 by the Lake Erie Walleye Task Group. Great Lakes Fishery Commission, Ann Arbor, Michigan.

Wang, H.-Y., Rutherford, E.S., Cook, H.A., Einhouse, D.W., Haas, R.C., Johnson, T.B., Kenyon, R., Locke, B., Turner, M.W., 2007. Movement of walleyes in Lakes Erie and St. Clair inferred from tag return and fisheries data. Trans. Am. Fish. Soc. 136, 539–551. https://doi.org/10.1577/t06-012.1

Whitmore, M.M., Litvak, M.K., 2018. Seasonal distribution and movement of juvenile Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) in the lower Saint John River Basin, New Brunswick, Canada. Can. J. Fish. Aquat. Sci. 75, 2354–2363. https://doi.org/10.1139/cjfas-2017-0429

Zhao, Y., Einhouse, D.W., MacDougall, T.M., 2011. Resolving some of the complexity of a mixed-origin walleye population in the east basin of Lake Erie using a mark–recapture study. North Am. J. Fish. Manag. 31, 379–389. https://doi.org/10.1080/02755947.2011.571516

Zhao, Y., Jones, M.L., Shuter, B.J., Roseman, E.F., 2009. A biophysical model of Lake Erie walleye (*Sander vitreus*) explains interannual variations in recruitment. Can. J. Fish. Aquat. Sci. 66, 114–125. https://doi.org/10.1139/F08-188

Zimmerman, D.W., Zumbo, B.D., 1993. Rank transformations and the power of the Student t test and Welch t-test for non-normal populations with unequal variances. Can. J. Exp. Psychol. 47, 523.

Appendices

Appendix A1: Acoustic transmitter and receiver supplementary information

Table A1.1: Original ID code of receivers deployed in southern Grand River compared to new labels given for this project.

Receiver ID	New label
LGR-013	RIF-13
LGR-009	RIF-9
LGR-005	RIF-5
LGR-006	RIF-6
LGR-012	RIF-12
LGR-011	RES-11
LGR-004	RES-4
LGR-010	DAM-10
LGR-003	DAM-3
LGR-007	DAM-7
LGR-001	PTM-1
LGR-002	PTM-2
LGR-008	BAY-8

Table A1.2: The number of walleye tagged with a transmitter having the given estimated tag life.

Estimated tag life	n
1825 days	224
2435 days	28
1667 days	1
1679 days	1
1701 days	1
1710 days	1
1742 days	1
1750 days	1
1777 days	1
397 days	1
25 days	1
48 days	1
51 days	1
57 days	1
61 days	1

70 days	1
87 days	1

Appendix A2: Walleye potentially filtered from acoustic telemetry detection data

Table A2.1: Walleye identified as having likely died due to repeated detection at a receiver (See Figure A2.1 for detection history).

Walleye ID	**Year tagged**	**Release location**	**Sex**	**Receiver with repeated detections**
58883001	2015	Above dam	Male	LGR-008
58886001	2015	Above dam	Male	LGR-001 and -002
58904001	2015	Below dam	Male	GRO-002
22874001	2015	Below dam	Female	EBP-022
22883001	2015	Below dam	Female	GRO-002
22889001	2015	Below dam	Female	LGR-007
56216001	2016	Above dam	Female	LGR-007
55327001	2016	Below dam	Female	LGR-008
50945001	2017	Above dam	Male	LGR-007

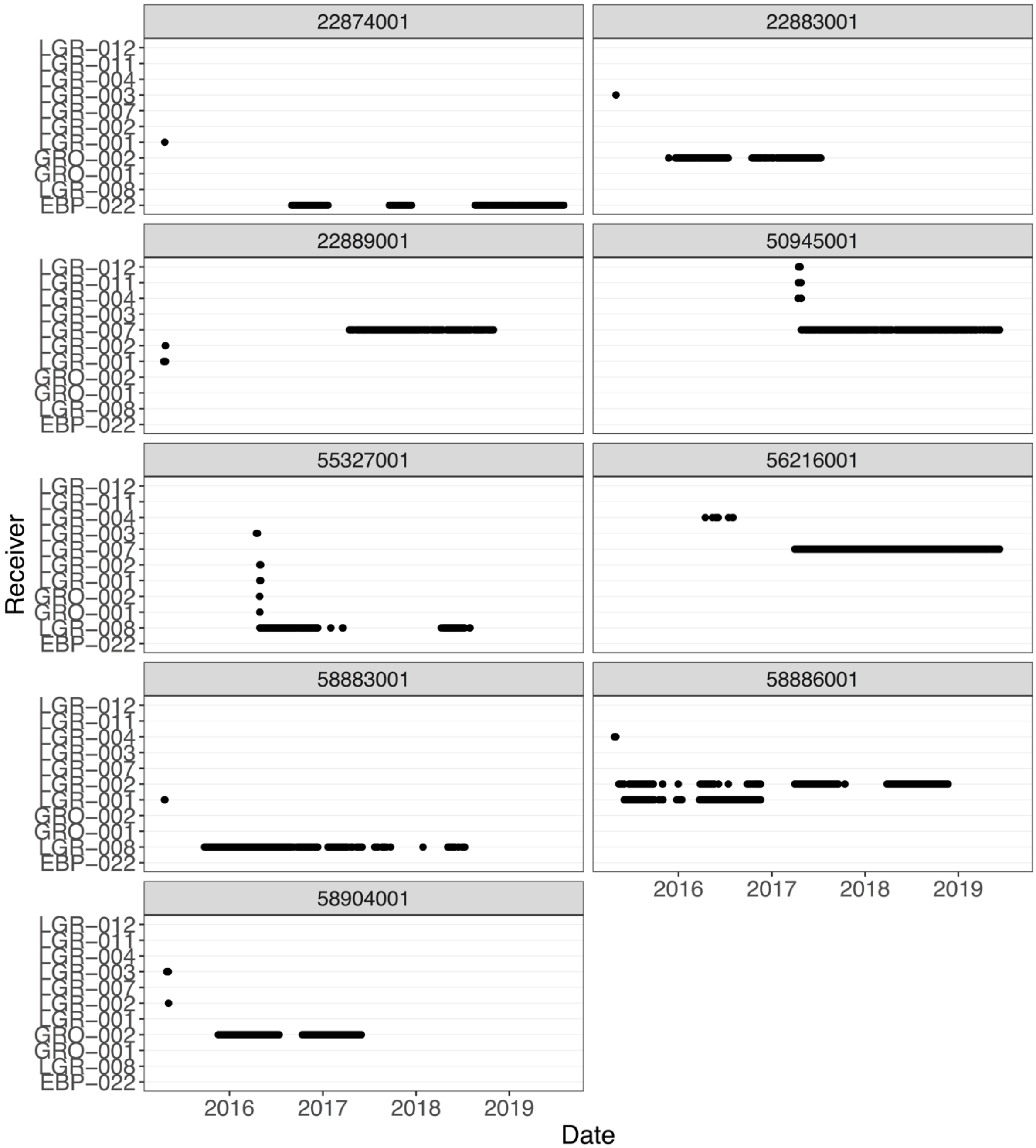

Figure A2.1: Detection history of walleye identified as having likely died (see Table A2.1).

Table A2.2: Walleye identified as having been detected above the Dunnville Dam for more than one year. (See Figure A2.2 for detection histories).

Walleye ID	Year tagged	Sex	Subsequent AD years
56174001	2016	Male	2017
56180001	2016	Male	2017
50946001	2017	Male	2018
56193002	2017	Female	2018
58898001	2015	Male	2018

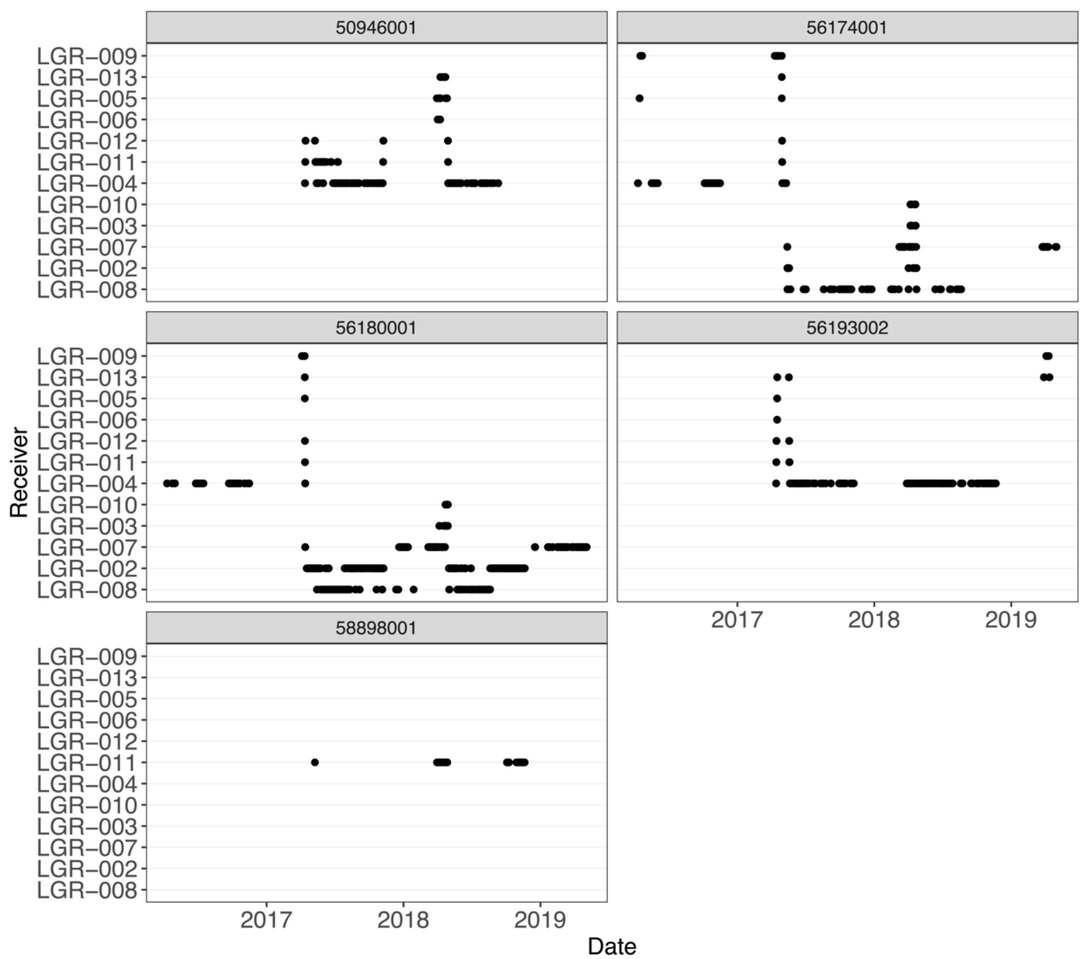

Figure A2.2: Detection history of walleye identified as having being detected above the Dunnville Dam for >1 year (see Table A2.2).

Appendix A3: Walleye residence time summary statistics

Table A3.1: Number (n) of male and female walleye that were released above the Dunnville Dam in 2017 and 2018 detected at eight receivers in the Grand River array, with mean and standard error (SE) total and log transformed residence time (res.time) in days.

Receiver	sex	n	Mean res.time	SE res.time	Mean log res.time	SE log res.time
RIF-13	F	16	0.68	0.30	-0.85	0.22
	M	14	1.20	0.51	-0.71	0.26
RIF-5	F	16	0.23	0.17	-1.31	0.16
	M	14	0.34	0.14	-1.10	0.23
RIF-12	F	33	0.47	0.24	-0.81	0.09
	M	31	0.40	0.11	-0.76	0.09
RES-11	F	33	0.51	0.19	-0.64	0.08
	M	35	0.77	0.29	-0.48	0.08
RES-4	F	33	2.52	0.91	-0.13	0.12
	M	40	2.36	0.81	-0.11	0.10
DAM-7	F	14	1.33	0.92	-0.81	0.24
	M	23	1.39	0.97	-0.99	0.18
PTM-2	F	15	1.49	0.61	-0.53	0.22
	M	21	0.73	0.27	-0.60	0.14
BAY-8	F	12	4.23	1.99	-0.07	0.28
	M	15	1.90	0.70	-0.07	0.18

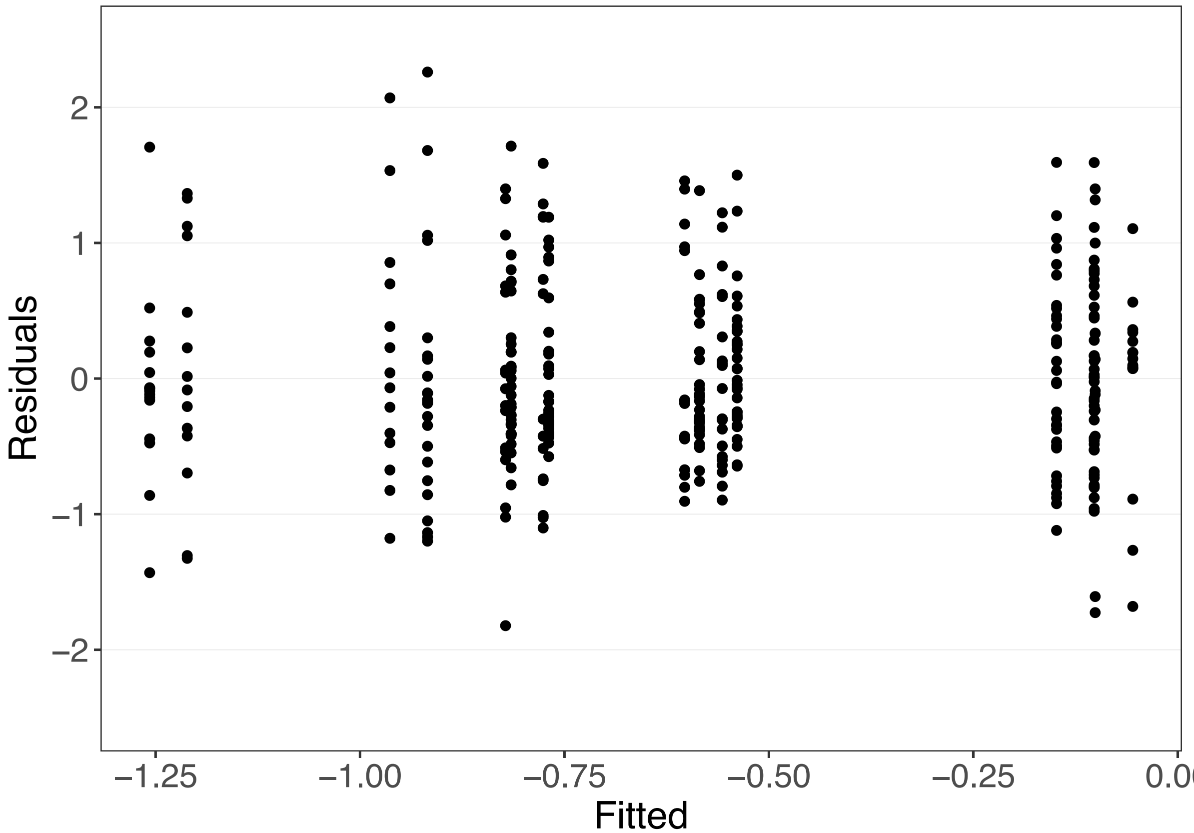

Figure A3.1: Residuals vs fitted values of log transformed total residence time in days among receivers in the southern Grand River, grouped by sex.

Appendix A4: Above dam walleye arrival time summary statistics

Table A4.1: Median arrival date and interquartile range (IQR) of walleye released above dam in 2017 and 2018 and receiver in the Grand River.

Year	Receiver	No. of walleye	Median arrival	IQR (days)
2017	RIF-9	3	2017-04-26	6.02
	RIF-13	11	2017-04-17	2.39
	RIF-5	12	2017-04-17	1.18
	RIF-6	6	2017-04-17	1.53
	RIF-12	31	2017-04-14	1.47
	RES-11	33	2017-04-13	1.47
	RES-4	38	2017-04-12	1.10
	DAM-10	2	2017-09-17	50.93
	DAM-3	3	2017-11-06	67.45
	DAM-7	19	2017-04-27	17.62
	PTM-2	18	2017-04-27	16.58
	BAY-8	17	2017-04-30	18.22
2018	RIF-9	11	2018-04-28	5.25
	RIF-13	19	2018-04-22	6.46
	RIF-5	18	2018-04-20	12.13
	RIF-6	6	2018-04-22	1.00
	RIF-12	34	2018-04-09	3.72
	RES-11	36	2018-04-08	3.43
	RES-4	36	2018-04-07	3.35
	DAM-10	2	2018-10-20	2.11
	DAM-3	3	2018-10-20	11.24
	DAM-7	23	2018-05-08	13.92
	PTM-2	22	2018-05-09	19.48
	BAY-8	16	2018-05-06	26.84

Appendix A5: DAM-3 detection history

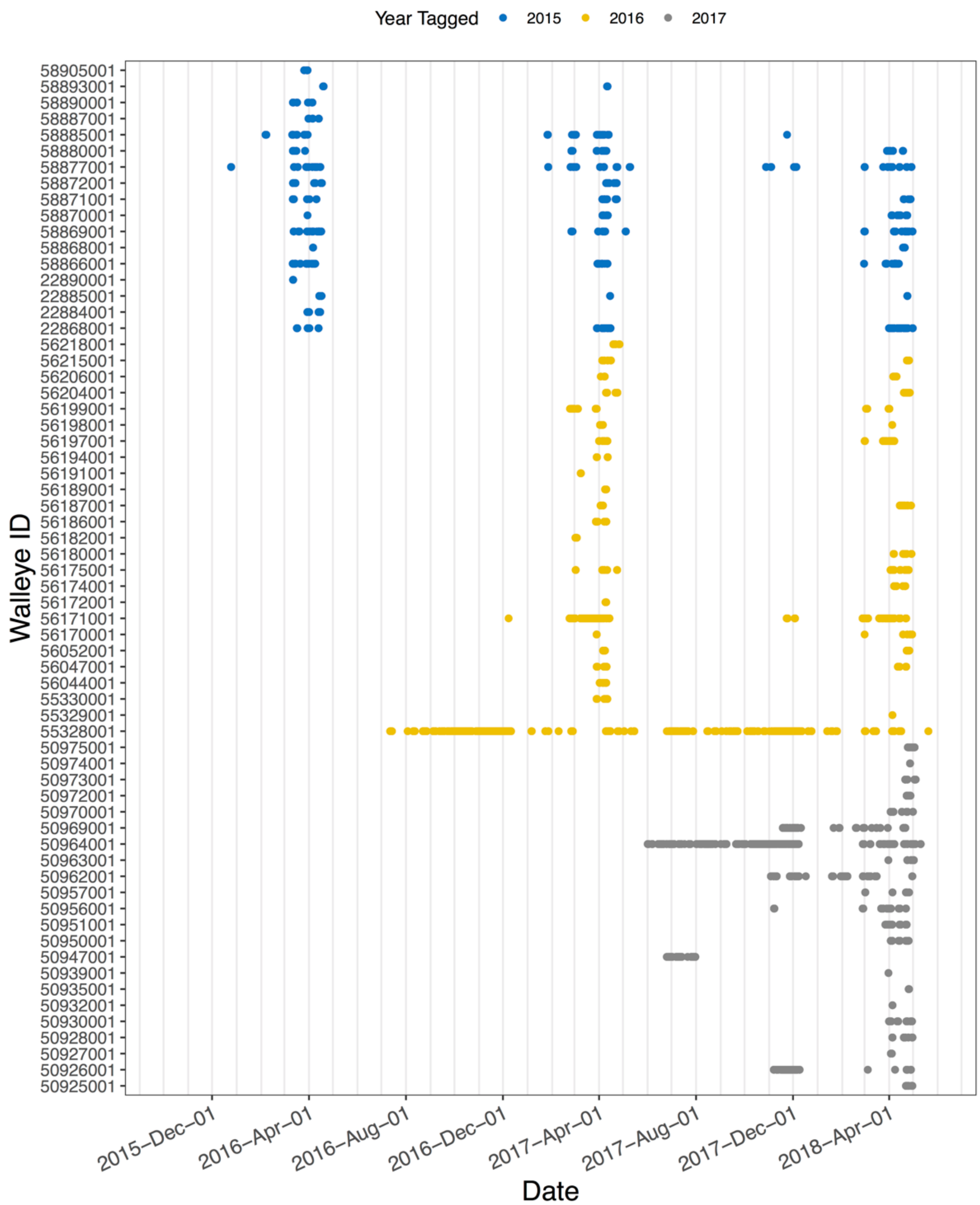

Figure A5.1: Detection history at the DAM-3 receiver of walleye that return to the Grand River in years subsequent to their initial spawning season. The year walleye were tagged is indicated by colour.

Appendix A6: Lake Erie arrays with detections from Grand River walleye

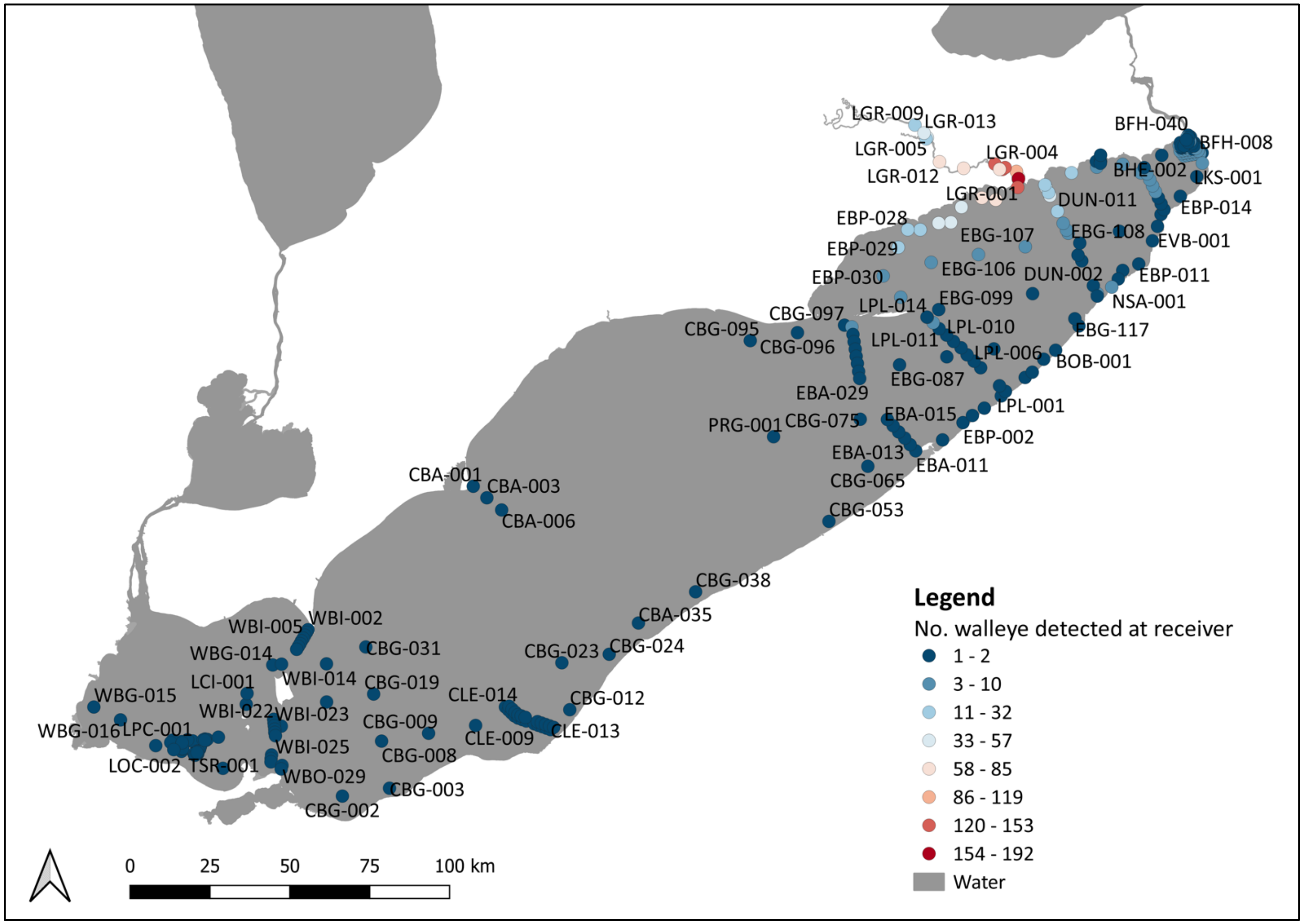

Figure A6.1: Number of Grand River walleye detected at Lake Erie arrays between 2015 and 2019.

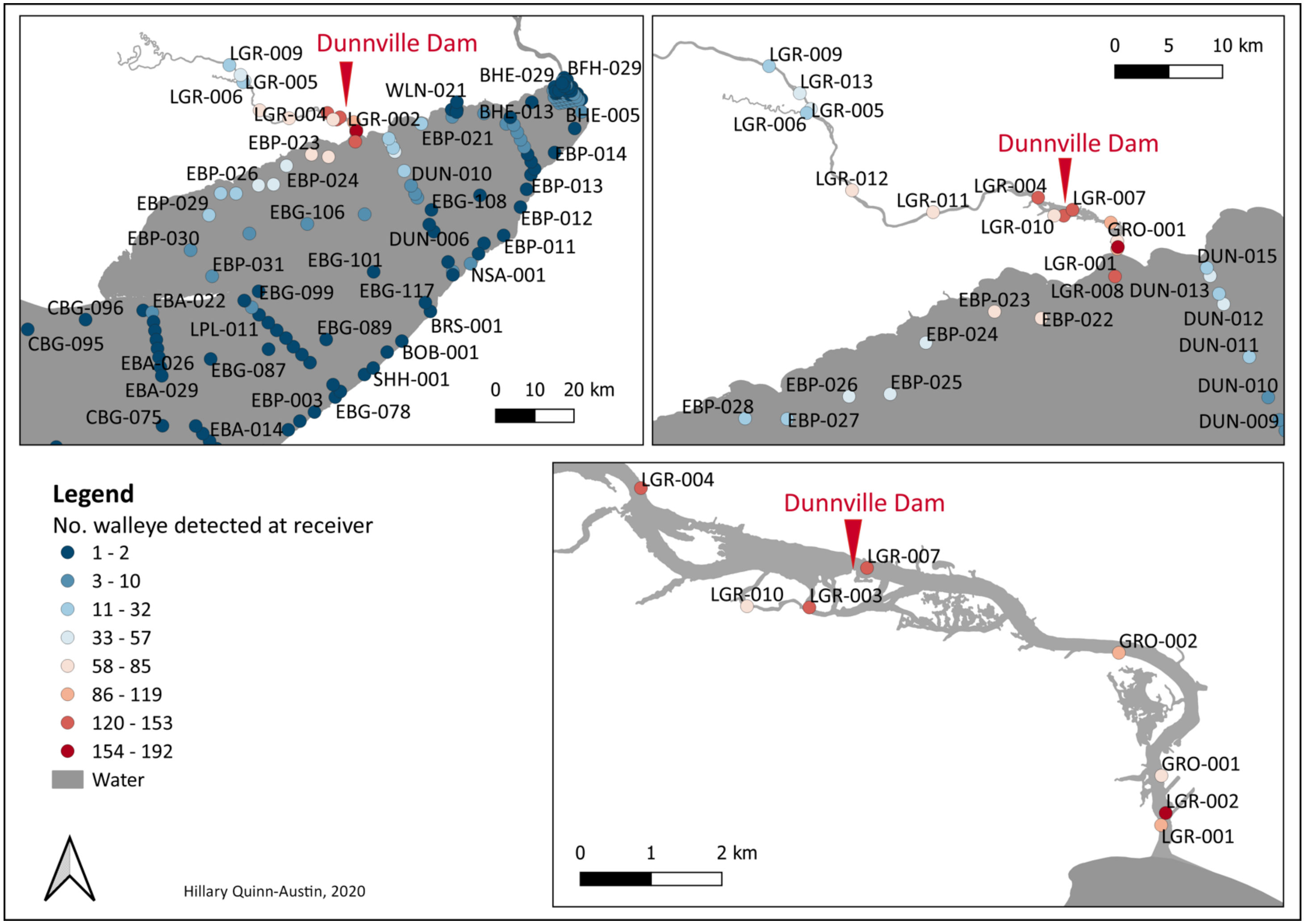

Figure A6.2: Number of Grand River walleye detected on Lake Erie arrays between 2015 and 2019 – three levels of zoom.

Appendix B1: YOY walleye summary statistics

Table B1.1: Mean and standard error (SE) of fork length (cm), weight (g), $\delta^{15}N$ and $\delta^{13}C$ (‰) for YOY walleye sampled from four sampling locations in the southern Grand River in September 2018 among each 1 km sampling transect, with shocker seconds, sample size (n), and CPUE (n/1000 s) given for each transect. A subset of the total sample size was used for stable isotope analyses (SIA).

Sampling location	Transect	Shocking seconds	n	CPUE	Mean length	SE length	Mean weight	SE weight	SIA sub-sample n	Mean $\delta^{15}N$	SE $\delta^{15}N$	Mean $\delta^{13}C$	SE $\delta^{13}C$
Riffle Transition	1	1277	10	8	16.9	0.4	44.4	3.0	10	18.5	0.1	-26.3	0.2
	2	1430	1	1	17.9	NA	58.5	NA	1	18.5	NA	-25.8	NA
	3	1627	10	6	17.2	0.4	46.4	3.5	10	18.5	0.1	-26.4	0.1
	4	1287	10	8	17.3	0.4	47.7	3.4	10	18.2	0.2	-26.1	0.1
Reservoir	1	1231	6	6	18.0	0.4	53.5	4.0	6	19.5	0.1	-27.4	0.1
	2	1103	3	3	18.6	0.6	62.5	4.6	3	19.7	0.1	-27.4	0.0
	3	1103	2	2	19.5	0.3	66.0	4.6	2	19.6	0.2	-26.8	0.2
	4	1148	2	2	18.2	0.7	57.5	8.8	2	18.7	0.1	-26.4	1.6
Below Dam	1	1000	12	12	18.0	0.2	54.2	2.2	10	18.8	0.1	-28.2	0.2
	2	1046	12	12	17.1	0.5	46.9	3.7	10	19.2	0.1	-28.5	0.1
	3	1039	30	30	17.6	0.2	51.8	2.0	9	18.8	0.1	-28.2	0.2
River Mouth	1	1241	10	10	20.0	0.6	82.9	6.4	10	18.3	0.2	-27.3	0.2
	2	1237	11	11	19.0	0.6	70.2	6.0	10	18.5	0.1	-27.9	0.1
	3	921	12	12	18.6	0.4	65.8	4.9	10	18.7	0.1	-28.2	0.1
	4	1108	13	13	18.2	0.3	59.4	3.0	11	18.7	0.1	-28.1	0.1

Table B1.2: Number (n) of YOY walleye sampled from four sampling locations in the southern Grand River in September 2019 among each 1 km sampling transect, with shocking seconds and CPUE (n/1000 s) given for each transect.

Sampling location	**Transect**	**Shocking seconds**	**n**	**CPUE (n/1000 s)**
Riffle Transition	1	1676	0	0
	2	1525	0	0
	3	1336	0	0
	4	1413	0	0
Reservoir	1	1306	0	0
	2	1035	0	0
	3	1342	0	0
	4	1268	0	0
Below Dam	1	562	0	0
	2	1346	2	1
	3	1236	2	2
River Mouth	1	899	2	2
	2	1499	2	1
	3	1702	2	1
	4	1045	4	4

Appendix B2: Residuals of linear models

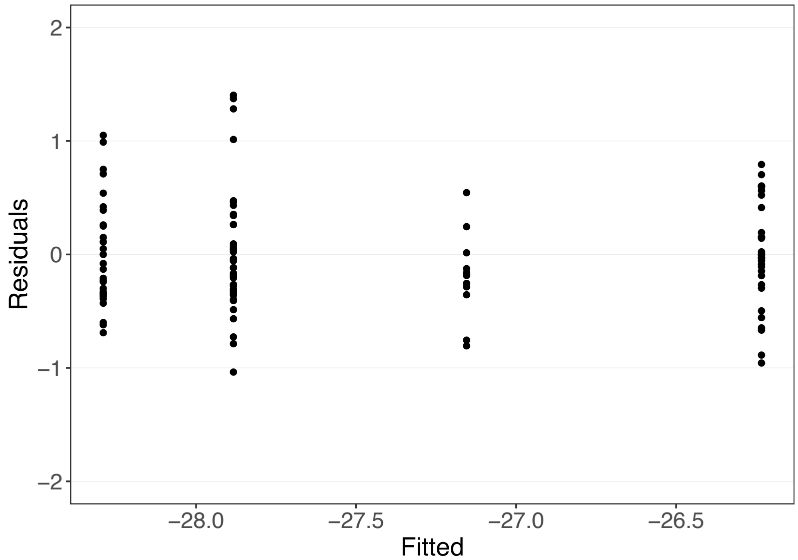

Figure B2.1: Residuals vs fitted values of YOY walleye $\delta^{13}C$ among four sampling locations from September 2018 in the southern Grand River.

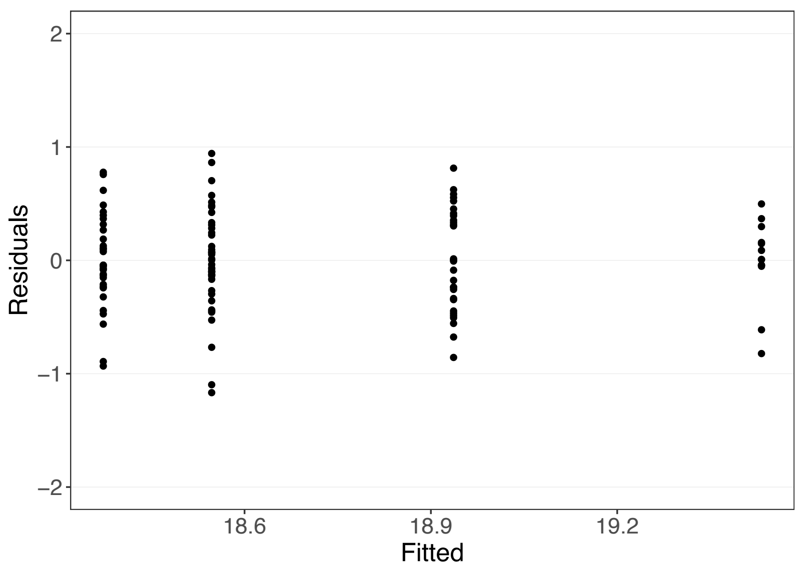

Figure B2.2: Residuals vs fitted values of YOY walleye $\delta^{15}N$ among four sampling locations from September 2018 in the southern Grand River.

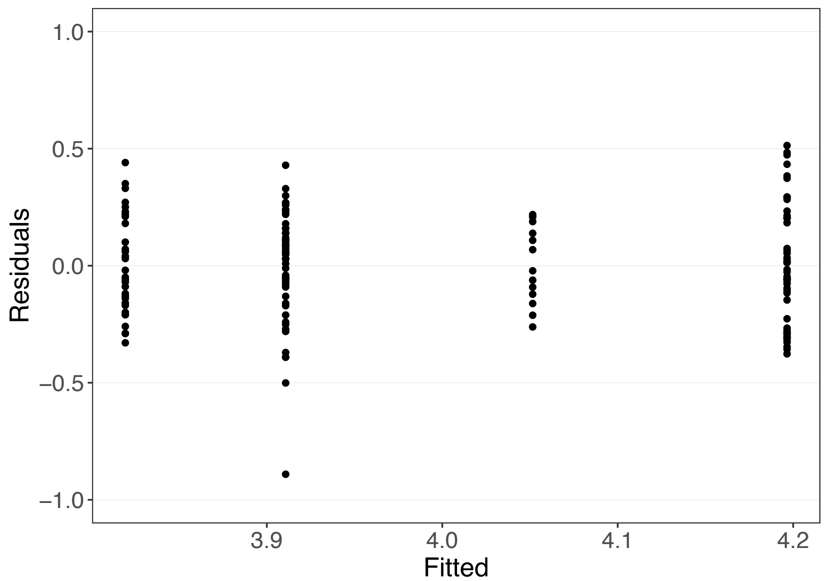

Figure B2.3: Residuals vs fitted values of YOY walleye log transformed weight among four sampling locations from September 2018 in the southern Grand River.

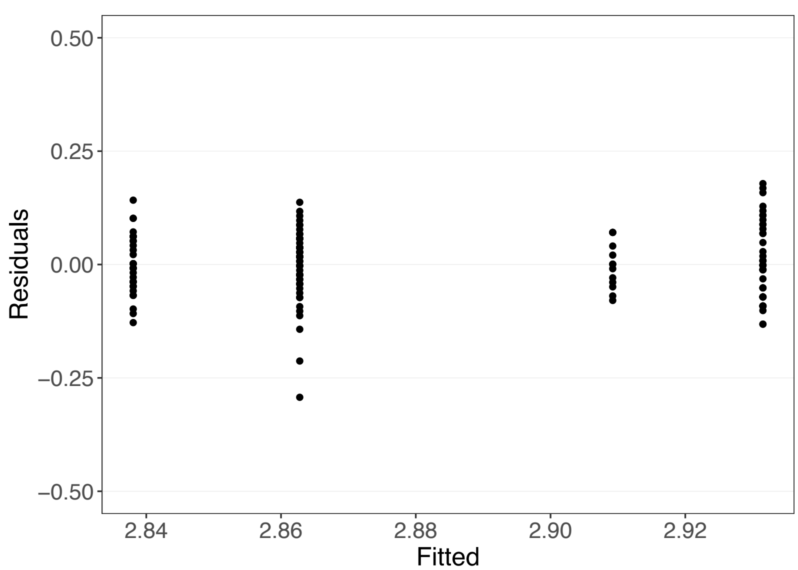

Figure B2.4: Residuals vs fitted values of YOY walleye log transformed length among four sampling locations from September 2018 in the southern Grand River.

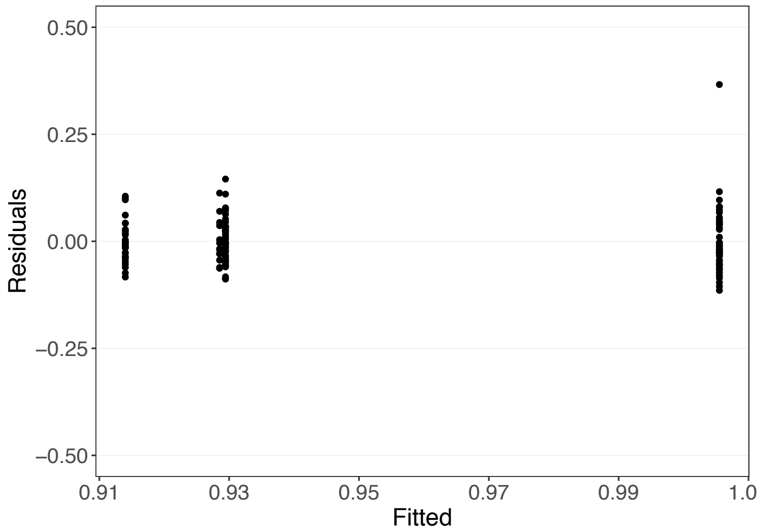

Figure B2.5: Residuals vs fitted values of YOY walleye condition among four sampling locations from September 2018 in the southern Grand River.

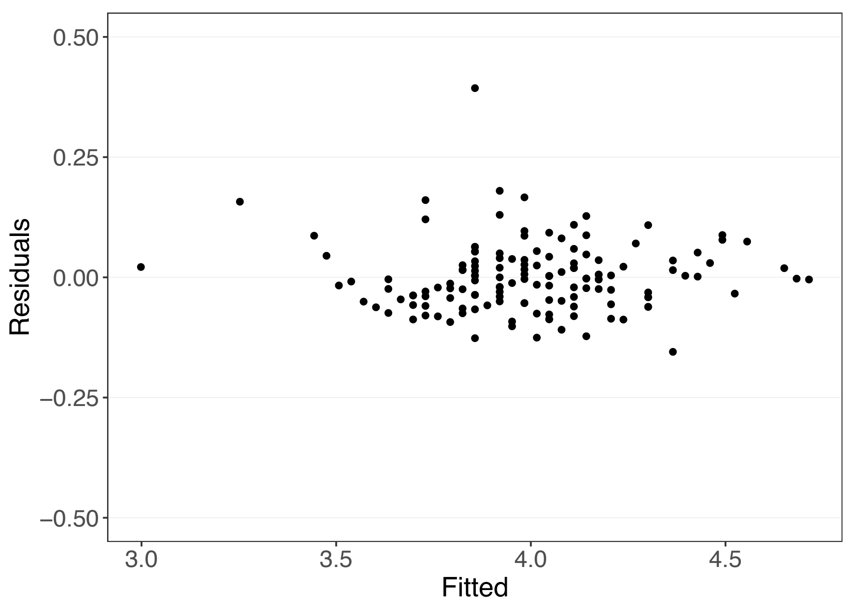

Figure B2.6: Residuals vs fitted values of the linear regression between log transformed length and log transformed weight of YOY walleye sampled in September 2018 from the southern Grand River.

Appendix B3: Coordinates of YOY walleye sampling locations

Table B3.1: Coordinates of YOY walleye sampling locations in the southern Grand River.

Sampling location	Transect	Latitude	Longitude
River mouth	1	N42°51.296'	W79°34.685'
	2	N42°51.914'	W79°34.503'
	3	N42°52.395'	W79°34.171'
	4	N42°52.934'	W79°34.248'
Below Dam	1	N42°53.121'	W79°34.934'
	2	N42°53.356'	W79°35.511'
	3	N42°53.750'	W79°36.028'
Reservoir	1	N42°54.112'	W79°37'336'
	2	N42°54.302'	W79°38.031'
	3	N42°45.532'	W79°38.684'
	4	N42°54.900'	W79°39.262'
Riffle Transition	1	N42°54.976'	W79°49.827'
	2	N42°55.516'	W79°50.085
	3	N42°55.844'	W79°50.357'
	4	N42°56.186'	W79°50.944'